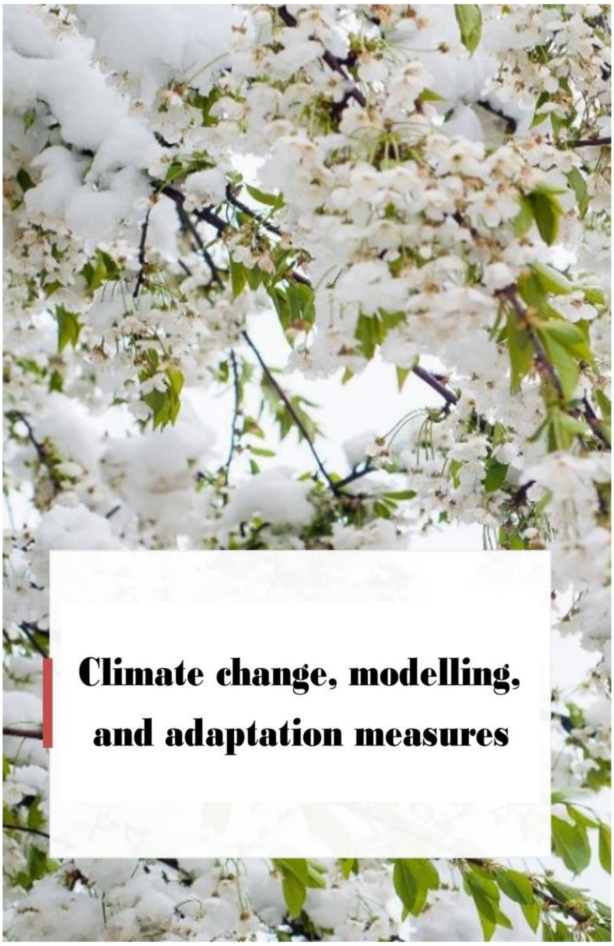

Climate change, modelling, and adaptation measures

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Ministry of Foreign Affairs of the Czech Republic

CZECH REPUBLIC DEVELOPMENT COOPERATION

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CLIMATE CHANGE, MODELLING, AND ADAPTATION MEASURES

LECTURES FOR STUDENTS

Digital Edition

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Md Rafique Ahasan Chawdhery

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Chapters 9–10: V. Potopová and M.R.A. Chawdhery
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CHIȘINĂU – 2022

Preface

Climate change is expected to affect regional and global food production through changes in overall agro-climatic conditions. Over the following decades, the warming trend in Europe is projected to lead to climatic conditions that significantly differ from today's climate. In line with the European Green Deal climate ambition, any new technology is expected to contribute to mitigation and adaptation to climate change and help achieve climate neutrality by 2050. Linking climate, economic, and growth models can be useful tools for predicting the development of the food production process in relation to climate change. The dynamic crop simulation models calculate expected growth and development based on equations describing how a crop responds to soil and weather conditions as a community of plants. Computer simulation models of the soil-plant-atmosphere system can contribute to improving crop performance and predicting environmental impacts in different management scenarios. Modelling suggests that climate change may affect crops in central Europe differently and that site conditions will determine whether yields will increase or decrease.

The authors are pleased to present supplementary resources for bachelor's and master's studies students in the Basic Meteorology and Climatology, and the Advanced Meteorology and Climatology courses, respectively. This textbook is also written for students taking an introductory course on climate change modelling and adaptation measures. The digital edition of this textbook is intended as a notice for graduate students in agroclimatic modelling to understand the concept of positive and negative climate feedback between the climate system and the agriculture system. This digital edition has been edited and corrected from the first printed edition.

These lecture notes can be fashioned by supplementing the text with readings from the current literature. This textbook is a non-commercial material. The later chapters of this textbook are informative for all who are interested in understanding the soil-plant-atmosphere relationships using the dynamic crop growth models and the Geographical Information System techniques.

CZECH REPUBLIC DEVELOPMENT COOPERATION

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Ministry of Foreign Affairs of the Czech Republic

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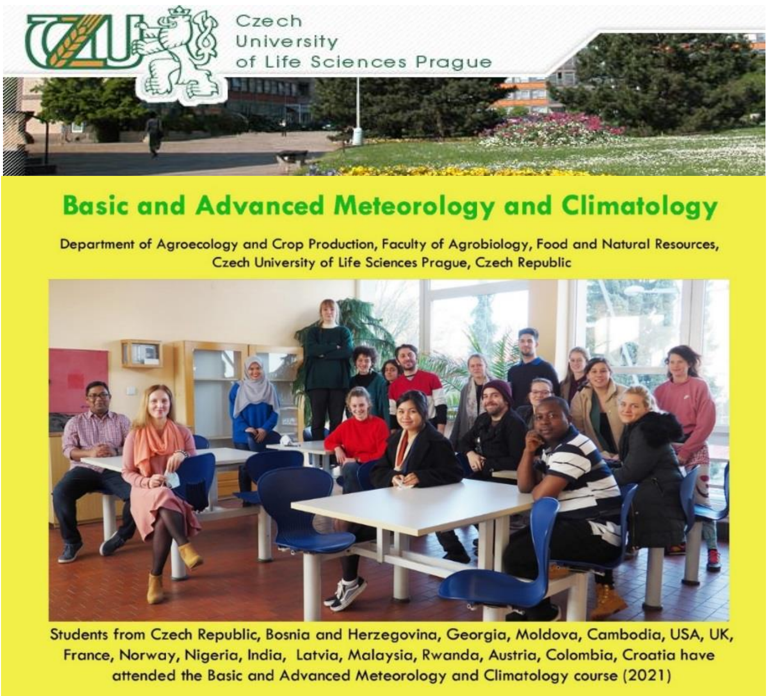

Reviews

An aspect of contemporary education that assumes the involvement of students in environmental research activities, and the subject of climate change is proving to be very actual. At present, we do believe that there is no doubt that the Earth's climate has suffered a major impact from the human factor, and the simple analysis of the chemical composition of atmospheric air, which the authors make in Chapter 2, comes with convincing evidence of the increase in the concentration of greenhouse gases. The originality of this work derives from the deviation from the excessive focus on theoretical knowledge to a practical approach to the surrounding reality. In this case, the processes occur in the terrestrial atmosphere, through the contribution of increasingly active anthropogenic pollution. To this end, the authors introduce several models of climate change analysis, as DSSAT - Decision Support System for Agrotechnology Transfer; HERMES - Highly Extensible Resource for Modelling Event-Driven Supply Chains; EPIC - Environmental Policy Integrated Climate; APEX - Agricultural Policy Environmental Extender; AquaCrop; APSIM - Agricultural Production System Simulator, etc. In order to obtain a product (e.g., map), or climate change indicator, the authors of the course, in a very effective way for students, propose to them a series of open-access databases (ECMWF, CCAFS-Climate data, WorldClim, UNEP Environmental Data Explorer, etc.) for climate change, adaptation measures, etc. A special approach is taken by the DSSAT model, described in detail by the authors in Chapter 9, where the difficult situations in the agricultural sector of the Czech Republic and the Republic of Moldova, can be modelled at the end including the need for water for irrigation per hectare, or the administration of fertilizers, as well as other useful indicators. Successfully the authors indicate the application steps in the development of the respective DSSAT model.

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Additional guidelines for basic courses, such as "Introduction to climate change, modelling, and adaptation measures", which are in themselves a well-structured synthesis of data and information related to climate change, their impact on the agricultural system, modelling principles and practical aspects can be found quite rarely in the university literature. This textbook completes in detail the necessary fundamental courses - meteorology and climatology. This textbook, consisting of 12 chapters, is organized as a guide, which starts with an analysis of the processes that take place in the atmosphere, their interaction with environmental components and ends with climate change, the principle of modelling and their applications. The information presented is well structured and rich in notions and indicators. The first 5 chapters focus on the justified analysis of these processes. Chapters 6-8 are devoted to the principles of climate change modelling focused more on the agricultural sector, more precisely on the production of agricultural crops. The last chapters 9-12 are examples of the possibility of using concrete models in assessing climate change, of which the possibilities of using GIS tools, described in chapters 11 and 12, are especially valuable. The accessible, easy-to-read language, organized at the fine line between science and popularization, adds value to this guide, and the rich set of synthetic statistics present in this book commends it to the permanent presence of student, master's, and young researchers table, who are interested in climate change processes and modelling.

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Table of Contents

Chapter 1

Introduction to the components of the climate system, their processes, and interactions

Keywords:

- climate system
- climate change
- change of weather
- climate feedback

Chapter 1: Introduction to the components of the climate system, their processes, and interactions

1.1 Fundamentals of weather and climate

- Meteorology – weather changes, the state of atmospheric properties for a given location.
    - from the Greek word *meteōros* – 'lofty, high (in the sky), i.e., "the study of things in the air"
    - Meteorologists study weather
- weather is defined as the atmosphere's state at a given place and time.
    - in other words: the short-term mode or operation of meteorological elements at a given location
    - basic feature: significant spatial and temporal variability
- meteorological elements: such physical quantities that we can measure (air temperature, humidity, total precipitation, wind speed and direction, values of radiation fluxes, etc.)
- meteorological phenomena: events taking place in the atmosphere (rainbow, lightning discharges), previously could not be measured, only observed
- weather forecasting – the application of technology to predict the state of the atmosphere for a given location

- collecting quantitative data about the current state of the atmosphere at a given place and using scientific understanding of atmospheric processes to project how the atmosphere will change:
  - on computer-based models that take many atmospheric factors into account

- Climatology is the study of climate.
  - from Greek *κλίμα*, Klima, "slope"; and – *λογία* – logia, "study"
  - the slope of the sun in the sky drove the climate
- Climate is defined in terms of the average weather elements over a specified period.
  - as the statistical description in terms of the mean and variability ranging from months to thousands or millions of years (the classical period for averaging these variables is 30 years)
  - long-term characteristic weather regime conditioned by energy balance, atmospheric circulation, nature of the active surface, and human activity
  - basic feature: relative stability

Climate Variability – denotes deviations from normal. It is measured by these deviations, which are usually termed anomalies.

Three properties of the climate include:

1. "normal" refers to average weather conditions in a place
2. "extremes" describe the maximum and minimum measurements of atmospheric variables
3. "frequencies" refers to the rate of incidence of a particular phenomenon at a specific place over a long period:
   - primarily concerned with exchanges in energy, mass, and momentum near the surface
   - emphasizes the nature of atmospheric energy and matter at climatic time scales
   - involves the processes of interaction between the atmosphere and near-surface water in all of its forms
   - primarily concerned with general atmospheric dynamics (the processes that induce atmospheric motion)
   - studies the relationships between the atmospheric circulation and the surface environment of a region
   - involves the extraction of climatic data from indirect sources
   - includes the interaction of living things with their atmospheric environment

1.2 What is climate change?

Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer).

What is the difference between climate variability and climate change?

- Climate variability – looks at changes within smaller timeframes (a month, a season, or a year).
- Climate change – considers changes that occur over a more extended period (over decades or longer).
- A critical difference between climate variability and change is in the persistence of "anomalous" conditions – when events that used to be rare occur more frequently.

Primary differences:

1) Time scales involved are different:
Meteorologists are primarily concerned with features of the atmosphere at a particular time and place (weather). Climatologists study the long-term patterns and trends of those short-term features (climate).
2) Climatology is inherently more intertwined with processes happening not just in the atmosphere but also in the other spheres:

- because the interactions between the atmosphere and other spheres are more likely to have significant consequences over more extended, rather than shorter, time scales.

Similarity:

- Weather/climate is driven by solar radiation, air pressure, temperature, and moisture differences between one place and another.
- These differences can occur due to the sun's angle at any spot, which varies by latitude from the tropics.
- Because the Earth's axis is tilted relative to its orbital plane, sunlight is incident at different angles at different times of the year.
- The strong temperature contrast between polar and tropical air gives rise to the jet stream.
- Weather systems in the mid-latitudes, such as extratropical cyclones, are caused by instabilities of the jet streamflow.

What is a phytoclimate?

- The microclimate of the environment where plants live and whose climatic conditions co-create (modify) their presence and life processes. It includes both the ground layer of the air, including the space above the vegetation affected by it and the, soil layer within reach of root systems.
- Therefore, the soil climate of the root space (rhizosphere climate) is an integral part of the stand climate.

What does the term global change mean?

- It is a wide range of biophysical, ecosystem, and socio-economic changes that alter the functioning of the Earth as a system on a planetary scale (changes in climate, land and ocean productivity, atmospheric chemistry, ecosystems).

What is global climate change?

- It is a change of climate attributed directly or indirectly to human activity that alters the composition of the global atmosphere and is in addition to natural climate variability observed over comparable time periods.

What is the Earth's climate system?

- It is a complex system consisting of five main components and their interrelationships. The climate system (CS) evolves over time. Its development has two causes. Firstly, CS development is influenced by its internal dynamics. Secondly, CS develops through external factors.

Why do we use global warming when cooling also occurs in some places?

Due to the balance of Earth's heat radiation. Earth emits less heat into space than it absorbs from the Sun. Therefore, it is heating up on a global scale.

What is abrupt climate change?

- The nonlinearity of the climate system may lead to abrupt climate change, sometimes called rapid climate change, short events, or even surprises.
- The term abrupt often refers to time scales faster than the typical time scale of the responsible forces.
- Some possible abrupt events that have been proposed include a dramatic reorganization of the *thermohaline circulation*, rapid deglaciation, and massive *melting of permafrost* or increases in soil respiration, leading to fast changes in the *carbon cycle*.

1.3 What is a climate proxy?

Climate proxies are variables that cannot be measured directly.

Sources of information – indirect data – come from natural records rather than instruments

1. paleometeorology (fossils)
2. dendroclimatology (tree trunks)
3. chronicles, archives, war news

- reliable global records of climate only began in the 1880s, and proxies provide the only means for scientists to determine climatic patterns before record-keeping began
- paleoclimatology ("paleo-" means past) – the study of previous climates during Earth's different geologic ages; for example, ice cores can be one example of climate proxies
- these indirect records of climatic conditions are *called proxy data*
- they make it possible to reconstruct the climatic conditions that prevailed in the Earth's past
- proxies can be combined to produce temperature reconstructions longer than the instrumental temperature record
- it can provide information on global warming and climate history

Why use ice cores?

- cylindrical samples obtained from ice sheets of high layers by drilling to depth in the Greenland, Antarctic, and North American regions
- the ratio between the ^{16}O and ^{18}O water molecule isotopes in an ice core helps determine past temperatures and snow accumulations
- the heavier isotope (^{18}O) condenses more readily as temperatures decrease and fall more easily as precipitation

- the lighter isotope (^{16}O) needs colder conditions to precipitate
- the farther north one needs to go to find elevated levels of the ^{18}O isotopes, the warmer the period.

1.4 What is the difference between climate change adaptation and mitigation?

1.1.1 Mitigation

- climate change mitigation or reducing climate change
- involves reducing the flow of heat-trapping greenhouse gases into the atmosphere, either by reducing sources of these gases or enhancing the "sinks" that accumulate and store these gases
- mitigation measures
    - stabilize greenhouse gas levels in a timeframe sufficient to allow ecosystems to adapt naturally to climate change
    - ensure that food production is not threatened
    - to enable economic development to proceed in a sustainable manner

1.1.2 Adaptation

- adapting to life in a changing climate – involves adjusting to actual or expected future climate
- adaptation measures:
    - to reduce our vulnerability to the harmful effects of climate change
    - encompasses making the most of any potential beneficial opportunities associated with climate change

1.5 The concept of positive and negative climate feedback on Earth's climate system

The Earth's climate system (CS) is influenced by various external forcing mechanisms, the most important solar radiation. An interactive system consisting of five major components: atmosphere, hydrosphere, lithosphere, cryosphere, and biosphere. Each component represents a complex heterogeneous open thermodynamic system in which many physical and chemical processes occur. The individual components constantly interact with each other; thus, matter and energy exchange.

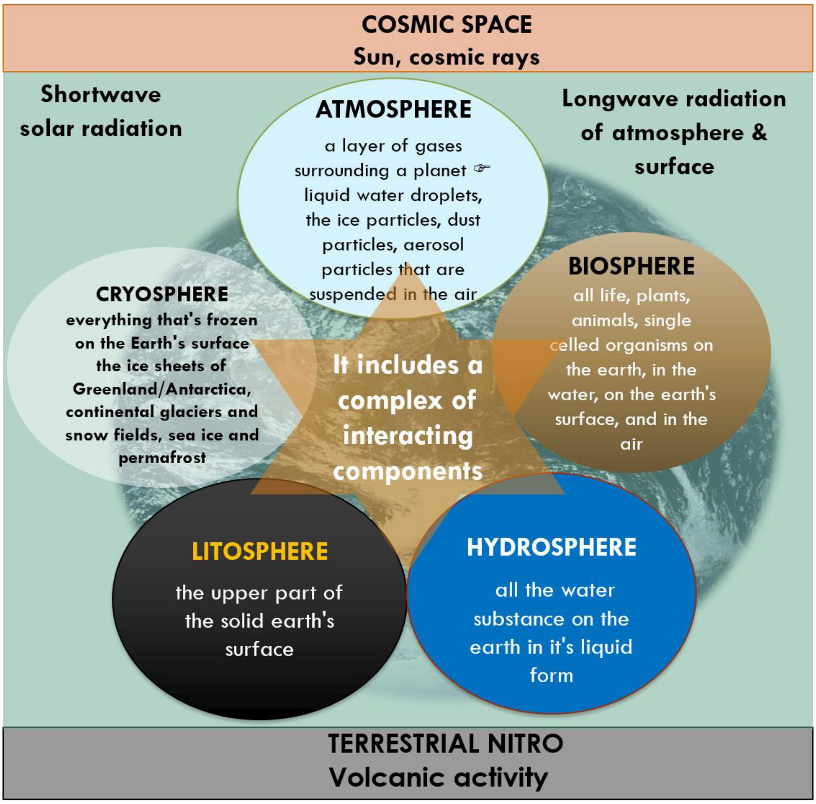
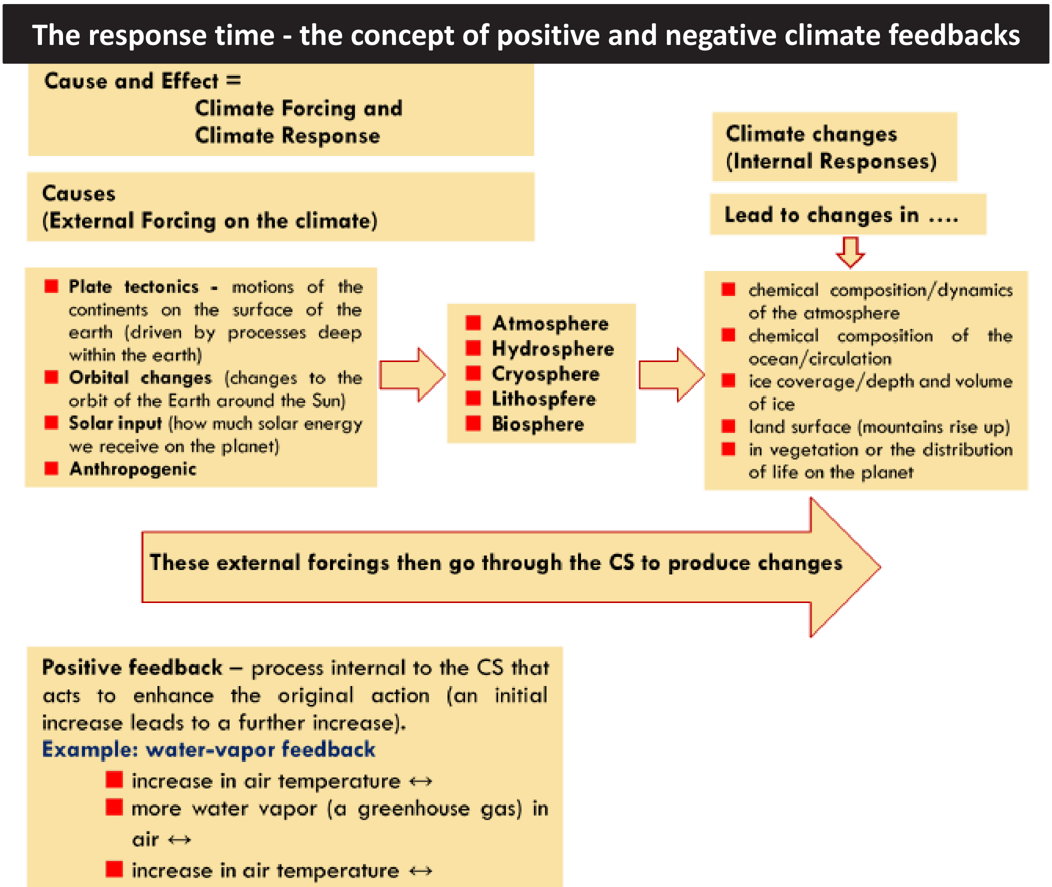


Fig. 1.1 Schematic view of the components of the CS, their processes, and interactions

The time needed for the CS to re-equilibrate to a new state, following a forcing resulting from external and internal processes or feedback.
The response time of the troposphere is relatively short, from days to weeks, whereas the stratosphere comes into equilibrium on a timescale of typically a few months. Due to their large heat capacity, the oceans have a much longer response time, typically decades, but up to centuries or millennia.

1.5.1 Feedback in the CS

Feedback – a term from electrical engineering. Part of the output from a particular system is returned and serves again as input, so the system's overall response changes. Thus, a change in one subsystem can cause a change in other components of the CS. The magnitude of the climate system's response to a specific external action-forcing (impulse). Climate sensitivity is sometimes referred to as a change in average global temperature caused by a doubling of the concentration of carbon dioxide in the atmosphere. Feedback changes the sensitivity of the climate to a particular forcing.



1.5.2 Ice-albedo feedback – feedback associated with snow and ice cover on the earth's surface

A. If the air temperature rises as a result of an impulse (e.g., an increase in the concentration of greenhouse gases), the surface area covered with snow or ice will decrease
B. This results in a reduction of the surface albedo, a reduction in the amount of reflected sunlight, which results in a further increase in air temperature
C. So, this is positive feedback

1.5.3 Water vapor feedback – feedback associated with water vapor in the atmosphere

A. An increase in air temperature due to some impulse (forcing) means an increase in evaporation and thus an increase in water vapor in the atmosphere
B. As water vapor is one of the most important greenhouse gases, this increase will result in a further increase in the air temperature at the earth's surface
C. This is again positive feedback

1.5.4 Cloud feedback – feedback associated with the amount of clouds

The effect of clouds on CS depends on many factors – on the type and height of clouds, on their optical properties, and on what kind of surface it is located.

A. The low-floor clouds have a high albedo; increasing their amount would cause a higher reflection of incident solar radiation at their upper limit and cool the earth's surface.
B. On the other hand, clouds increase the greenhouse effect, so the surface temperature should increase, which should at least partially dampen the cooling due to the increase in albedo.
C. In the case of high clouds, it is assumed that the effect of intensifying the greenhouse effect prevails, so an increase in sky cover with high clouds could increase the air temperature.

1.5.5 Feedback of increase in CO_2 concentration leads to increase in temperature

A. An increase in the temperature of the Earth's surface results in increased heat radiation and thus the cooling of the Earth's surface.

B. The greenhouse effect dampens the effect of this feedback.

C. Increase in CO_2 concentration – increase in ocean temperature – decreased ability of the ocean to absorb CO_2 – increase in CO_2 concentration in the atmosphere.

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Chapter 2

Changes in the atmospheric composition

Keywords:

- lapse rate
- greenhouse effect
- global warming potential
- ozone hole
- radiative forcing of greenhouse gases

Chapter 2: Changes in the atmospheric composition

2.1 Size of Earth's Atmosphere

A. air

1. air: a mixture of gases around the earth
2. pure air is invisible; gases in it are colorless, odorless, and tasteless

B. the atmosphere

1. the atmosphere surrounds Earth, to which it is held by gravitational attraction
2. > 98% of the mass of the atmosphere is within 32 km of sea level
3. atmosphere extends downward into crevices in rocks and soil
4. mass approx. 5.157 x 10^{18} kg (a million times lighter than planet Earth)
5. extending up to 1000–1200 km (but already around 600–800 km; we can talk about a vacuum)

The atmosphere protects:

- life on Earth by absorbing ultraviolet solar radiation (O_3)
- warming the surface through heat retention (greenhouse effect)
- reducing t °C extremes between day and night (the diurnal temperature variations)

Absence of atmosphere

- black sky with shining stars (scattering of sunlight on air molecules)
- without clouds (they are formed by condensation or desublimation of water vapor - it would not be there)
- substantial temperature fluctuations between day and night (high short-wave radiation consumption during the day and significant emission of long-wave radiation during the night)
- silence (sound is mechanical waves that do not propagate in a vacuum)
- sharp contrasts between irradiated and non-irradiated areas (there would be no light scattering)
- without twilight sunset & dusk (there would be no reflection of rays from the atmosphere)

Twilight is the illumination of the lower atmosphere when the Sun is not directly visible because it is below the horizon (there is still light in the sky)

Dusk is when the sun is at 18 degrees below the horizon, and there is no longer any sunlight in the sky.

2.2 Composition of the atmosphere

A. Constant Gases – have relatively long residence times in the atmosphere and occur in uniform proportions across the globe and upward through the bulk of the atmosphere

1. Nitrogen and Oxygen

a. nitrogen

1) 78% volume of dry air
2) added by decay and burning of organic matter, volcanic eruptions, and chemical breakdown of certain rocks
3) dilutes oxygen and prevents rapid burning at the earth's surface
4) living things need it to make proteins
5) nitrogen cannot be used directly from the air
6) nitrogen cycle is nature's way of supplying the needed nitrogen for living things

b. oxygen

1) 21% volume of dry air
2) produced by vegetation
3) it is necessary for combustion or burning

c. argon = 0.943% $\Rightarrow$ used in light bulbs

d. trace gases: neon, helium, methane, krypton, hydrogen

e. atmospheric concentration does not change
f. minimal effect on weather and climate

B. Variable Gases – sparse but highly variable atmospheric quantities; significant influence on weather & climate
1. WATER VAPOUR
a. determines humidity of the atmosphere
b. 0 – 4% of the total volume
   1) highest in air overlying warm, moist surfaces, such as tropical oceans
   2) lowest over deserts and in polar regions
   3) listed as a variable gas, but it is variable in location, not in time
   4) total amount in the atmosphere as a whole remains virtually constant
c. significant influence on weather and climate
   1) source of all clouds and precipitation
   2) impacts heating and cooling processes

2. CARBON DIOXIDE (CO_2)
   a. 390 ppm $\Rightarrow$ in 2020 = 412.5 ppm
   b. concentration increasing (2 ppm per year), a result of increased burning of fossil fuels
   c. significant influence on weather and climate
1) absorbs infrared radiation
2) increase the concentration $\Rightarrow$ of global climate change

Parts per million (ppm):

A unit of measurement that can be used to describe the concentration of a particular substance within the air. For example, the concentration of CO_2 in the Earth's atmosphere is almost 400 parts per million, which means 1 million litters of air would contain about 400 litres of CO_2

One mill air = 400 litres CO_2

3. OZONE (O_3)
   a. a minor but vital gas
   b. concentrated in the ozone layer (25-35 km above Earth's surface)
   c. absorbs ultraviolet radiation (99%)
   d. increasing concentrations of various hydrocarbons from automobile and factory emissions

C. Particulates

1. particulates = aerosols: solid and liquid particles in the atmosphere
   a. natural sources: volcanic ash, windblown soil and pollen grains, wildfire smoke, salt spray
   b. human sources: industrial and auto emissions, smoke, and soot
2. influence weather and climate
   a. hygroscopic: water vapour condenses around condensation nuclei → cloud formation
   b. absorb or reflect sunlight ⇒ decrease solar energy reaching earth

Table 1 Atmospheric composition

gas	formula	% vol.	persistence
nitrogen	N_2	78.08	20 million years
oxygen	O_2	20.95	3–10 this. years
argon	Ar	0.94	stable
carbon dioxide	CO_2	0.41	2-10 years
neon	Ne	0.0018	stable
helium	He	0.0005	10 million years
methane	CH_4	0.0002	2-10 years
krypton	Kr	0.0001	stable
hydrogen	H_2	0.00005	4-8 years
nitrous oxide	N_2O	0.00005	5-200 years
xenon	Xe	0.000007	stable
ozone	O_3	0.000007	2 years

Source: Gatley et al., 2008

2.3 Vertical structure of the atmosphere

Three criteria:

1) Thermal structure: troposphere, stratosphere, mesosphere, and thermosphere
2) Composition: homosphere and heterosphere
3) Function: ozonosphere and ionosphere

1) Thermal Layers

- ✓ the lower portion of the atmosphere is the zone in which most weather phenomena occur
- ✓ pause: the boundary between layers, the pause layers are neutral (no temperature change with height)

Troposphere

   a. sea level – 20 km
   b. zone of vertical mixing and turbulence
   c. depth varies
      1) deepest over tropical regions (20 km); shallowest over poles (7 km)
      2) deeper in summer than winter

d. tropopause: top of the troposphere

- it contains about 75% of the weight of the atmosphere
- it contains almost all water vapour in the atmosphere (99%)
- 50% of the water vapour is in the ground layer up to a height of 1.5 km (due to sources on the earth's surface and due to the air temperature - warm air can hold more water vapour)

The stratosphere is the second layer

a. 8 – 50 km ⇒ it starts at the equator=18 km; poles≈8 km; mid-latitudes=10-13 km and ends at 50 km.
b. "ozone layer" - is warm because it absorbs UV rays from the sun
c. isothermal layer (10–25 km) → no convection (air does not flow upwards), temperature -50 to -60 °C
d. temperature inversion layer - from 30 km T increase with height (approx. 0 °C at the upper limit)
e. stratopause: top of the stratosphere

The mesosphere is above the stratosphere

a. 50 – 80 km
b. mesopause: top of the mesosphere

Thermosphere

a. 80 – 800 km
b. temperature cannot be measured by classical thermometric methods → low particle density

Exosphere

a. 800 – 40 000 km
b. transitions freely into interplanetary space, free hydrogen, and helium atoms leave the atmosphere due to low gravity

Physico-chemical processes:

The transition region between the neutrosphere and the ionosphere is between 70 and 90 km, depending on latitude and season.

Neutrosphere – in this layer, for the most part, not ionised, that is, electrically neutral.

Ionosphere – the ionized part of Earth's upper atmosphere.

a. deep layer of electrically charged molecules and atoms
b. middle-upper mesosphere and lower thermosphere
c. aid long-distance communication by reflecting radio waves
d. auroral displays – northern lights

The effect is caused by the interaction of charged particles from the Sun with atoms in the upper atmosphere. A natural electrical phenomenon is characterised by the appearance of streamers of reddish or greenish light in the sky, especially near the northern or southern magnetic pole.

Prediction of the state of the ionosphere is important for telecommunications, radio, and communication with orbiting satellites or GPS. Disorders in the ionosphere can result in reduced reliability of navigation systems or impaired communication with orbiting satellites.

2.4 Temperature patterns in the atmosphere

Air temperature changes with altitude

lapse rate – decreases with 0.65°C/100m (because of the decreasing compression of atmospheric gases with increasing distance from the surface and increasing distance from the heat source – the surface)

a. troposphere:

1) air temperature decreases with increasing altitude (to -57 °C at tropopause)

2) heat source at ground level: solar energy absorbed by Earth's surface

3) tropopause: temperature remains constant

b. stratosphere:

1) air temperature increases with increasing altitude

2) heat source: ozone layer where O_3 absorbs ultraviolet radiation and warms the atmosphere

c. mesosphere: air temperature decreases with increasing altitude

1) air temperature reaches a minimum at the top of the mesosphere

d. thermosphere:

1) temperature increases with increasing altitude

2) heat source: splitting and heating of atoms and molecules that absorb ultraviolet radiation

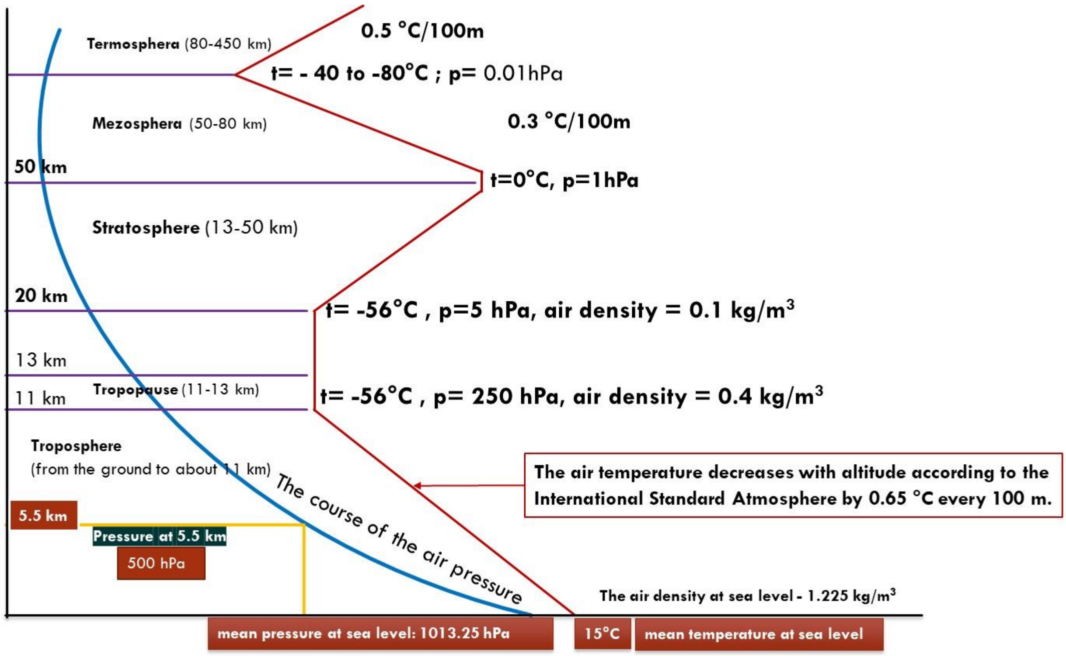

Fig. 2.1 Schematic view of the temperature and pressure changes with elevation in the atmosphere

2.5 Composition: Homosphere and Heterosphere

1. homosphere

a. principal gases uniformly distributed

b. turbulent mixing causes the atmospheric composition to be pretty homogenous from the surface to ~80-90 km

2. heterosphere

a. above 90 km

b. much lower density

c. gases layered by their molecular masses from heaviest to lightest: nitrogen, oxygen, helium, and hydrogen

d. water vapour

e. diminishes with increasing altitude

f. >16 km, the atmosphere so cold, any moisture has already frozen → no clouds

The ozonosphere

- part of the stratosphere
- 15-30 km
- contains a more significant proportion of O_3 to O_2 (maximum ozone at the height of 22-23 km)

- absorbs mainly UVB radiation
- formation of ozone: UV radiation or lightning discharges split O_2 into two O (Oxygen) atoms, and they then react with O_2 to form O_3
- the amount of ozone is measured in DU (Dobson unit)
- a column of air with an ozone concentration of 1DU would contain about 2.69×10^{16} ozone molecules for every square centimetre of the area at the base of the column
- over the Earth's surface, the O_3 layer's average thickness is about 300 DU, or a layer that is 3 millimetres thick
- it is damaged by chlorinated and fluorinated hydrocarbons (freons)

Ozone layer damage – the ozone hole

- arises from the degradation of ozone by chemicals of predominantly anthropogenic origin, especially CFCs (chlorofluorocarbons) - fire extinguishers, cooling systems
- is defined by a value of 220 DU
- halogenated hydrocarbons (freons) release chlorine, which cleaves O_3 molecules
- the synthesis of O_3 in the stratosphere by UV radiation cannot compensate for losses
- it is formed mainly during the polar winter over Antarctica, where very cold stratospheric air is isolated, and the catalytic reactions of chlorine and bromine take place for a long time; the air is not mixed with air from latitudes closer to the equator
- in polar summer, the air is mixed with air from lower latitudes which are rich in ozone, and the ozone hole will heal

$$O_3 + X \rightarrow XO + O_2$$

X - chlorine, and bromine radicals (formed by UV radiation - cleavage of free radicals)

- the source of radicals are freons (CFC, HCFC) and halons (H substituted by Br)
- radicals formed by the action of UV radiation on halogenated hydrocarbons

- polar stratospheric clouds form at very low temperatures (-78 °C) and affect ozone degradation
- polar vortex – prevents mixing of the air from warmer areas

$$Cl\cdot + O_3 \rightarrow ClO\cdot + O_2$$
$$ClO\cdot + O_3 \rightarrow 2O_2 + Cl\cdot$$

Effects of tropospheric ozone

- occurs in the lowest layers of the troposphere (up to several tens of max. hundreds of meters)
- makes up 10-20 % of the total amount of ozone in the atmosphere
- increased concentrations of tropospheric ozone damage not only plants but also animals, including humans, as well as many technical materials
- is one of the gases that, in higher concentrations, negatively affects human health
- causes eye, nasopharyngeal irritation, and inflammation of the respiratory tract
- it is formed by chemical reactions of nitrogen oxides with volatile organic compounds on hot summer days and with no wind, especially in urban and industrial areas
- tropospheric ozone concentrations are so high in large areas of Europe and the United States that not only human health is endangered, but also vegetation is severely disturbed

2.6 Greenhouse effect

- essential part of life on Earth
- radiation-active gases cause it in the atmosphere (these gases are heteronuclear)
- radiation-active gases absorb the long-wave radiation of the Earth and thus increase their temperature
- greenhouse gases: H_2O (60 %), CO_2 (26 %), CH_4, N_2O, O_3, CFC (absorption spectra overlap)
- the most important greenhouse gas of natural origin is water vapour (it contributes 60 % to the greenhouse effect)
- CO_2 is the most important greenhouse gas of anthropogenic origin, but increasing its concentration in the atmosphere leads to an undesirable intensification of the greenhouse effect (it contributes 26 % to the greenhouse effect)
- without the greenhouse effect, the air temperature at the earth's surface would be -18 °C (today, the temperature is +15 °C)

2.6.1 GWP - Global Warming Potential

- it is the heat absorbed by greenhouse gases in the atmosphere, as a multiple of the heat that the same mass of CO_2 would absorb
- expresses the potential of individual gases for global warming
- CO_2 remains in the climate system for a very long time: CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years
- the GWP depends on two things:

- how effective the gas is at trapping heat while it's in the atmosphere
- how long it stays in the atmosphere before it breaks down
- for example: CH_4 breaks down quite quickly, and the average methane molecule stays in the atmosphere for around 12 years

2.6.2 Main anthropogenic sources of greenhouse gases

Carbon dioxide (CO_2):

- increase in concentrations by 31 % since 1750 – this concentration has not been exceeded in the last 420 thousand years and probably also 20 million years
- the current rate of increase has no analogy for at least 20,000 years – 75 % of anthropogenic CO_2 emissions in the last 20 years come from burning fossil fuels, the rest from land-use changes (deforestation)
- the ocean and land absorb about half of the anthropogenic CO_2 emissions
- fluctuations in annual CO_2 increments are related to climate variability and changes in remission and release from land and oceans

Methane (CH_4):

- increase in concentrations since 1750 by 151 % and continues - current concentrations not reached in the last 420 thousand years – in the 90s compared to the 80s, the increase in concentrations slowed and became more variable – just over half of the current CH_4 emissions are of anthropogenic origin

Nitrous oxide (N_2O):

- compared to 1750, the concentration increases by 17 % and continues – current concentrations have not been exceeded in the last 1000 years – about a third of current N_2O emissions are of anthropogenic origin

Ozone (O_3):

- decrease in O_3 in the stratosphere results in negative radiation effects – O_3 concentrations in the troposphere has increased by 36 % since 1750, mainly due to anthropogenic emissions of ozone-producing gases - positive O_3 radiation effects are significantly regionally variable and respond much faster to changes in emissions than other GHGs.

2.6.3 Changes in CO_2 concentration

- the evolution of carbon dioxide emissions changes during the year
- the most significant production of CO_2 is from fossil fuels in the most populated areas of the world
- large production of CO_2 occurs in China and the USA, mainly from industrial activities and the burning of fossil fuels

- there are seasonal changes in the concentration of CO_2 in the context of the seasons relative to latitude
- significant variability within the northern hemisphere (which has relatively more landmass and terrestrial vegetation) than in the southern hemisphere (which is more dominated by oceans)
- the farther we are from the equator, the greater the seasonal variability
- period of dormancy vs vegetation period when CO_2 is consumed by photosynthesis
- plants take more CO_2 from the atmosphere during the warmer months when they are growing the most which leads to noticeably lower CO_2 concentrations in the atmosphere
- cellular respiration occurs all the time but dominates during the colder months of the year, resulting in higher CO_2 levels in the atmosphere during those months

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Chapter 3

Energy balance of the Earth's climate system

Keywords:

- spectrum of solar radiation
- absorption of radiation by gases
- solar constant
- radiation scattering
- direct radiation
- diffuse radiation
- reflected radiation
- global radiation
- albedo

Chapter 3: Energy balance of the Earth's climate system

Two significant energy sources in the earth-atmosphere system are Solar Energy (99.97%) and Geothermal Energy (0.03%). Solar energy is produced in the sun by thermonuclear reactions. Geothermal energy comes from the Earth's interior and is produced by radioactive minerals decay. Energy from these sources supports life on earth and drives all atmospheric and weather processes. Without the sun's unequal heating of the planet, there would be no need for the atmosphere/oceans to circulate because no differences in energy would be received from one place to another on the earth's surface.

3.1 The Sun as energy source

- thermonuclear reactions in the Sun are the same ones in the most powerful hydrogen bomb: hydrogen (H) is converted into helium (He) (releases ENERGY)
- every second, at the core of the Sun, 560 Mt of *H* is converted to 556 Mt of *He*, thus releasing energy in the form of radiation
- energy is released because the *He* nucleus has a slightly lower mass than the four *H* nuclei
- when converting 1g of *H* to 1g of *He*, the energy released is equivalent to burning 15 tonnes of gasoline

How long does it take sunlight to reach the Earth?

We orbit the Sun at a distance of about 150 million km. Light moves at 300,000 kilometres/second. Divide these, and you get 500 seconds or 8.3 minutes.

3.2 Electromagnetic radiation

Solar heat energy travels through space in the form of electromagnetic waves enabling heat transferring a process known as radiation. Radiation is spread unevenly across all wavelengths. Electromagnetic waves use charged particles (such as electrons) to move up and down. These waves have electrical and magnetic properties and can travel through gases, liquids, solids, and space (or a vacuum). Electromagnetic waves are characterized by their wavelengths and frequencies. Wavelength (λ, m) is the distance between two wave crests. Frequency (f, Hz) refers to the number of wavelengths that pass a fixed point in 1 second.

The wave speed (v, ms^{-1}) is calculated by multiplying the wavelength and frequency. Wavelength is inversely proportional to frequency i.e., the shorter the wavelength, the higher its frequency.

3.3 Division of electromagnetic radiation according to wavelength

- radio waves (0.1–2000 m) – radio, television
- microwaves (0.3 mm–0.1 m) – mobile phones, GPS, Wi-Fi, microwave ovens, radars
- infrared radiation (750 nm–0.3 mm) – remote controls, night vision, thermal radiation
- visible radiation (390–750 nm) – visible light has colour components
- ultraviolet radiation (10–390 nm) – tanning, solariums, sterilization
- X-rays (1 pm –10 nm) – medical diagnostics, industrial diagnostics
- gamma radiation (<300 pm) – tumour irradiation, cosmic radiation, nuclear reactors

Ionizing and non-ionizing radiation

- ionizing radiation has such high energy that it can eject electrons from the atomic shell and thus ionize molecules
- in plants and animals, ionizing radiation has a destructive effect because it disrupts the genetic code and creates natural mutations
- examples of ionizing radiation are gamma radiation, X-rays, UVC (Ultraviolet C), and UVB (Ultraviolet B) radiation
- examples of non-ionizing radiation are UVA (Ultraviolet A), visible, infrared radiation, microwaves, and radio waves – these wavelengths do not cause ionization of molecules

3.4 Characteristics of radiation incident on the earth's surface

For the practical needs of meteorology and climatology, we distinguish only two types of radiation:

- shortwave - wavelength <4 μ m, makes up 99% of the Sun's electromagnetic radiation
- longwave - wavelength> 4 μ m, radiation of the Earth's surface and atmosphere

3.4.1 Ultraviolet radiation

- wavelength (λ) 0.01–0.4 μ m (10–400 nm)
- it is invisible to humans, but some animals perceive it (birds, reptiles, or insects)
- significant for humans in the impact on the skin (melanoma formation)
- use: disinfection of surfaces (in laboratories), excitation of phosphors (protective elements of banknotes), UV composites in dentistry
- UV division:
    - extreme UV radiation (λ = 10–100 nm)
        - participates in the chemical processes of the ionosphere, does not fall on the earth's surface
    - UVC radiation (λ = 100–280 nm)
        - does not fall to the earth's surface
    - UVB radiation (λ = 280–320 nm)
        - it is largely absorbed by the ozone layer but falls on the earth's surface
        - its impact on human skin causes the production of vitamin D
        - in case of intense sun exposure without protective equipment causes skin burns
        - it can also cause the development of melanomas or eye damage
    - UVA (λ = 320–400 nm)
        - it is not affected by the ozone layer; it falls on the earth's surface
        - penetrates the deeper layers of the skin and causes its tan
        - destroys collagen fibres, gradually loses skin elasticity, and wrinkles form and deepen
        - causes the production of free radicals in the deeper layers of the skin – an increased risk of melanoma

3.4.2 Visible radiation (light)

- wavelength 380-750 nm
- it is not absorbed in the atmosphere and therefore falls on the earth's surface
- plants use it for photosynthesis and animals to obtain information about their surroundings visually
- the part with a wavelength of 400-700 nm is called photosynthetically active radiation (FAR)
- divided into individual colour areas - blue (λ =450–475 nm), green (λ = 495–570 nm), red (λ = 620–750 nm)

3.4.3 Infrared radiation

- wavelength 750 nm - 400 μ m
- we perceive some of its wavelengths as heat

- it passes through the Earth's atmosphere only partially in the so-called windows - some of its wavelengths are absorbed by water vapour and carbon dioxide
- according to the wavelength, it can be divided into near, thermal, and far-infrared radiation
- use:
  - infrared radiators and infrared lamps
  - mobile phones, remote controls (transmission of information over short distances)
  - thermovision (remote sensing of objects or animals)
  - motion sensors, remote sensing, space exploration

3.5 Selected physical laws related to electromagnetic radiation

3.5.1 Stephan-Boltzmann's law

$$I = \varepsilon \cdot \sigma \cdot T^4$$

- T – the temperature in Kelvin
- σ - Stefan-Boltzmann constant ($5.67.10^{-8}$ W $m^{-2}K^{-4}$)
- ε - emissivity
- I - radiant emittance

- everybody that has a non-zero thermodynamic temperature is a radiator
- the higher the body temperature, the more energy it radiates
- the sun has a surface temperature of 6000 K and emits radiation with a wavelength of 0.2–4 μ m with a maximum emission of about 0.5 μ m (higher radiation energy)
- the earth has an average surface temperature of 15 °C and emits radiation with a wavelength of λ = 4–100 μ m with a maximum of about 10 μ m (less radiation energy)

3.5.2 Wien's law of displacement

- with increasing radiator temperature, the maximum value of the spectral density of the radiant flux shifts to shorter wavelengths
- the warmer the body, the more the wavelength of the radiation that the body emits, the most will decrease.
  For example: we see the sun yellow because its surface temperature is 6000 K, which means that its maximum radiation is in the region of about 500 nm, which is the yellow region of the visible spectrum

3.6 Solar radiation at the upper limit of the atmosphere

- at the upper limit of the atmosphere approximately constant amount of solar radiation exists; thus, the solar constant
- value of solar constant = approx. 1366 W m^{-2}
- the solar constant may vary plus or minus 3.5% about the changing Earth-Sun distance
- also changes in connection with the 11-year solar cycle

- the share of individual components of solar radiation at the upper limit of the atmosphere is:
    - 5% ultraviolet radiation
    - 28% visible radiation
    - 67% infrared radiation
- as it passes through the atmosphere, some components are absorbed, so the radiation on the earth's surface has a different composition
    - 2% ultraviolet radiation
    - 43% visible radiation
    - 53% infrared radiation

3.7 Factors influencing the amount of sunlight falling on the earth's surface

3.7.1 Factors related to the properties of the Sun and the Earth's orbit around the Sun

- solar cycle (development and extinction of sunspots)
- change in the shape of the Earth's orbit (Milankovič cycles)
- the tilt of the Earth's axis (influence on the input of solar radiation at individual places on the Earth)
- time of day and season (connection with the rotation of the Earth and its movement around the Sun)

3.7.2 Factors related to atmospheric properties

- absorption of radiation by the atmosphere
    - radiation of some wavelengths is absorbed in the atmosphere by various gases or aerosols
    - water vapour and carbon dioxide absorb infrared radiation
    - ozone absorbs UVB radiation
    - Lambert-Beer's law also applies to the passage of radiation through the atmosphere (it expresses the dependence of the absorption of radiation on the thickness of the layer through which the radiation passes)

- scattering of radiation by the atmosphere
- two types of variance:
- *Rayleigh scattering* - scattering on air molecules
    - is inversely proportional to the square of the wavelength of the radiation
    - radiation with a shorter wavelength is scattered significantly more than radiation with a longer wavelength
    - the consequence of this scattering is the blue colour of the sky (the blue colour has the shortest wavelength in the visible spectrum)
- *Mie scattering* - scattering on larger particles (water drops, ice crystals, dust particles)
    - it results in the grey colour of the clouds

The orange to the red coloured sky at sunrise or sunset is caused by the fact that the sun is low above the horizon and the rays must pass through the atmosphere over a longer path. During this passage of radiation through the atmosphere, shorter wavelengths scatter and radiation with a longer wavelength falls on the earth's surface, corresponding to orange and red.

- clouds
    - causes significant variability in the amount of sunlight falling on the earth's surface
    - we do not see the sun with increased clouds - only diffuse radiation falls on the earth's surface
    - the effect on solar radiation depends on the type, extent and distribution of clouds
- air pollution
    - chemical-physical-biological state in the Earth's atmosphere caused by an increase in the amount of pollutants in the atmosphere, which hurts human health or the environment
    - pollutants are usually gaseous (NO_x, SO_2) or solid (airborne dust)
    - these substances can have both natural and anthropogenic origins
    - aerosols and dust particles cause more significant scattering of radiation and thus cause an overall reduction in the amount of incident sunlight

3.7.3 Factors related to the properties of the earth's surface

- geographical location
    - in general, the closer a place is to the equator, the more sunlight falls on the earth's surface
    - in Europe: the average annual amount of sunshine in southern Spain is about two times greater than south Sweden and Denmark
    - locations with the highest yearly sum of solar radiation are in the vicinity of the tropics (there is increased cloud cover on the equator, which blocks solar radiation)
- altitude
    - as the altitude increases, the proportion of the ultraviolet component increases
    - in high mountains, the sky is dark blue - the path of the sun's rays is shorter and there is no such significant scattering of radiation
- albedo of a surface
    - degree of surface reflectivity
    - we express it either by a decimal number in the range 0 to 1 or as a percentage
    - the ratio of the reflected shortwave radiation from the active surface to the incident radiation
    - changes with the angle of incidence of sunlight
    - the average albedo of the Earth is 37-39 %

<u>albedo of individual surfaces:</u>

- fresh snow 80-95 %
- meadows 25-30 %
- forests and fields 10–25 %
- asphalt 5-10 % (90-95 % absorbed by incident radiation)
- dark roofs 8-18 %
- water surfaces - dependence of albedo on the angle of incident radiation (small-angle - large albedo)

3.8 Components of radiation balance

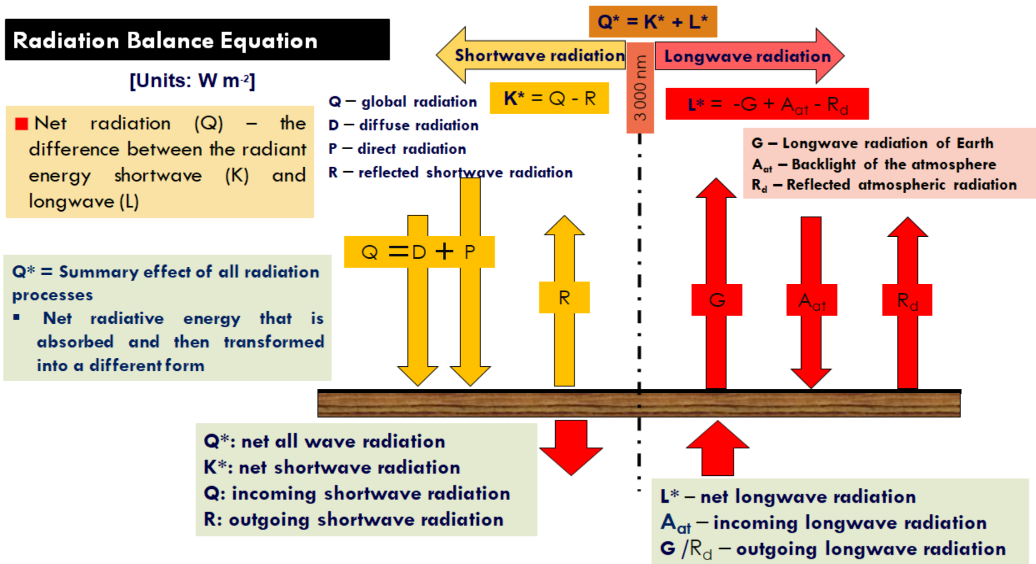

Fig. 3.1 Schematic view of the components of radiation balance

3.8.1 Global radiation

- the sum of direct and diffuse solar radiation incident on a horizontal surface at the level of the earth's surface
- its intensity is usually given in units of W m^{-2} and it is measured with a pyranometer
- in the cloudless days, mainly direct radiation occurs
- during cloudy days, it is formed exclusively by scattered (diffuse radiation)
- its composition depends on the position of the Sun and the clouds:
    - before sunrise, Q consists only of scattered radiation
    - direct radiation also appears from the moment of sunrise
    - in the morning, direct radiation increases
    - in the afternoon, the proportion of direct radiation decreases and at the same time the proportion of scattered radiation increases

3.8.2 Direct radiation

- such radiation that falls on the earth's surface directly from the Sun and therefore does not scatter in the atmosphere
- the path of the point at which the sun's rays strike and the sun in the sky is a straight line
- the values of the intensity of direct radiation change not only during the day and year but also according to the slope and orientation of the relief

3.8.3 Diffuse radiation

- it is omnidirectional; it has the same intensity in all directions
- it falls on the earth's surface after a change of direction due to scattering in the atmosphere
- during cloudy days, only this radiation falls on the earth's surface
- its share is also higher if the Sun is low above the horizon (the path of the ray is longer – a more significant scattering of radiation)
- in the winter months, the share of diffuse radiation is higher, and the share of direct radiation increases in summer
- it is measured with a pyranometer, which is shaded by a shielding circle

3.8.4 Reflected radiation

- the part of the shortwave radiation that is reflected from the surface or air particles or water droplets back into the atmosphere
- its intensity depends on the albedo of the surface, its colour and structure
- radiation can also be reflected from the atmosphere

3.8.5 Long-wave radiation of the Earth

- radiated by the earth's surface and all objects on it
- the intensity of the radiation depends on Stephan-Boltzmann’s law
- not only the earth's surface but also gases in the atmosphere participate in the radiation (this radiation is called backscattering of the atmosphere)
- the earth's surface and atmosphere emit infrared radiation
- if this radiation has such a wavelength that it is absorbed by CO_2 or water vapour, it remains trapped in the atmosphere in the form of an increase in the temperature of these gases - the greenhouse effect

3.8.6 Total radiation balance

<u>shortwave balance</u>:

- energy balance on the Earth's surface = direct radiation + diffuse radiation - reflected radiation

<u>longwave balance</u>:

- energy balance on the Earth's surface = backscatter of the atmosphere - long-wave radiation of the Earth - reflected radiation of the atmosphere
- 100 % solar radiation at the upper limit of the atmosphere

- 25 % reflected by the atmosphere, 5 % reflected the by surface
- 25 % absorbed by atmosphere
- 45 % absorbed by the surface
    - 12 % greenhouse effect
    - 23 % evaporation
    - 5 % convection
    - 4 % surface radiation
    - 0.2 % wind and waves
    - 0.08 % photosynthesis
- in the end, 45 % of the absorbed energy is radiated in the form of infrared radiation into space

3.9 Duration of sunshine

- the time interval between sunrise and sunset when direct solar radiation has an intensity higher than 120 Wm^{-2}
- it depends on the length of the day, clouds, and obstacles overshadowing the measurement site
- detected by heliographs - glass sphere + spherical bowl with paper tape

3.10 Use of solar radiation by plants

- plants absorb
    - 99 % of incident ultraviolet radiation
    - 90 % of visible radiation in the blue-violet and red-orange spectral areas
    - 50 % of visible radiation in the green region (this spectral region is most reflected - we see them as green)
- PhAR (Photosynthesis active radiation) after impact on the surface of the plant:
    - reflected from 6-12 %
    - 10-20% passes through plants
    - absorbed from 60-80 %
    - 1-3% used for photosynthesis
- distribution of plants according to the requirements for the intensity of incident solar radiation:
    - <u>heliophyte (light-loving plants)</u>
        - they grow in open sunny habitats
        - they have few chloroplasts
        - frequent presence of trichomes – a reflection of sunlight
    - <u>sciophyta (shade-loving plants)</u>
        - grow in the undergrowth (e.g. forests)

- they use radiation more efficiently than heliophytes
- morphological adaptations - horizontal position of leaves, one layer of leaves
- leaves dark green or reddish
- contain more red photosynthetically active pigments

- effects of PhAR on plants:
  - photosynthetic – the process of photosynthesis (change of light radiation energy into chemical bond energy)
  - photomorphogenesis – radiation acts as a regulator of growth processes
    - plants respond to changes in the composition of incident sunlight
    - plants have a large number of photoreceptors
      - phytochromes capture visible red radiation
      - cryptochromes and phototropins (blue-light receptors that serve to optimize the photosynthetic efficiency of plants) are sensitive to blue and UVA radiation
    - UVR8 receptors capture the UVB portion of the light spectrum
    - information obtained by photoreceptors is necessary for several developmental and physiological processes:
      - germination, shadow avoidance, phototropism, leaf development, flowering, and movements of chloroplasts lead to the optimization of their position to ensure the reception of the optimal amount of light radiation, etc.
  - thermal – most of the radiation absorbed by the plant is converted into heat, which is then removed by transpiration

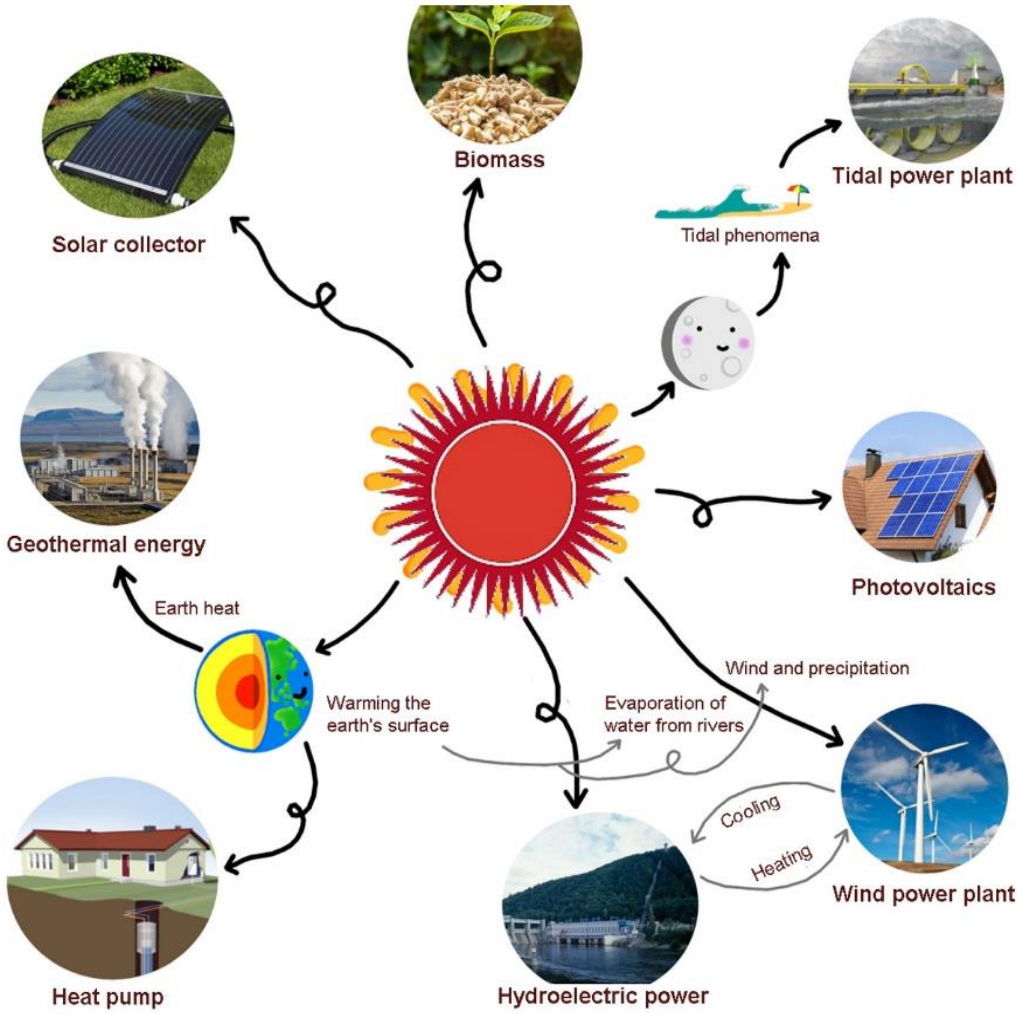

Fig. 3.2 Importance of solar radiation on the environment and human activities

3.11 Human use of solar radiation

- Solar Panels
- photovoltaic power plants
- solar grill
- solar furnace (concentrating the sun's rays in one place with a parabolic mirror)
- low-energy houses
- solar-powered cars
- solar motorway (Fig. 3.2)

Presentation of the SoDa website http://www.soda-pro.com/

Radiation: solar radiation database (HelioClim-1, CAMS McClear, CAMS radiation service)

Spectral: spectral radiation database, UV

Altitude: altitude of a particular place

Astronomy: calculation of solar angles for a given locality

Atmosphere: cloud statistics, aerosol optical depth

Meteorological data: MERRA, GFS Forecast

Typical years: typical years or monthly averages (cloud type, air temperature and relative humidity)

Validation: it is possible to verify the quality of own data obtained by ground measurements

Ch3 Sources:

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Chapter 4

Thermal regime of the atmosphere, soil, air, and water temperature. Heat balance of ecosystems

Keywords:

- heat and temperature
- definition of temperature, scale
- conduction, convection and radiation
- thermal conductivity, heat capacity
- specific, latent heat
- black frost
- ground frost

Chapter 4: Thermal regime of the atmosphere, soil, air, and water temperature. Heat balance of ecosystems

4.1 Physical quantities of Heat and Temperature

- two different physical quantities
- different units (°C, J)
- Heat ⇒ the total energy of molecular motion in a substance that flows from a warmer object to a cooler one.
    - It describes a change in the thermodynamic state of the system (exchange energy).
- Temperature ⇒ the value expressing the measure of the mean kinetic energy of the moving particles of a given mass.
    - It describes the state of the system.

Temperature units

- the base is Kelvin, defined based on the triple point of water
- other units °C (Andres Celsius, used in most parts of the world)
- °F (degrees Fahrenheit, USA)
- Celsius scale today: 0 °C corresponds to the solidification value of water at a pressure of 1013.25 hPa and 100 °C corresponds to the boiling of water at a pressure of 1013.25 hPa

- change of state is a reaction in which energy is consumed in one process and energy is released in the opposite process (gaseous – liquid – gaseous – heat is consumed; gaseous – liquid – solid – heat is released)

Heat units:

- J (joule) ⇒ 1 N·m (the energy transferred to an object when a force of 1 N acts on that object in the direction of its motion through a distance of one metre)

4.2 Heat transfer

Moisture in the atmosphere is continually changing its physical state:

Solid	Liquid	Gas
⟷	⟷	⟷
(ice)	(water)	(vapour)

⟶

Heat Energy Required (Melting, Evaporation) = cooling

⟵

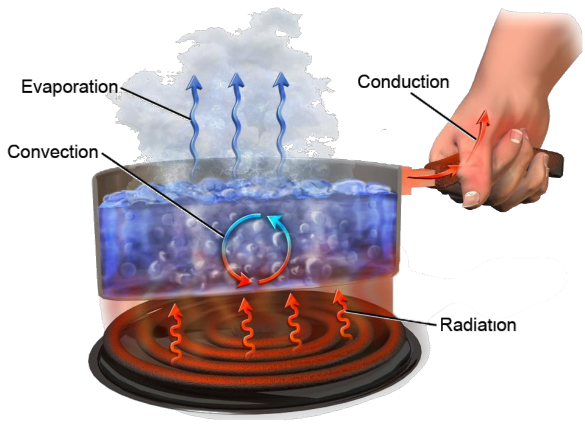
Heat Energy Released (Condensation, Freezing) = warming

Convection

- In physics, heat transfer through fluid flow, as opposed to heat conduction and radiation.
- In meteorology, the term is used specifically to describe the vertical transport of heat and moisture in the atmosphere, especially by updrafts and downdrafts in an unstable atmosphere
- Elevated convection occurs within an elevated layer, i.e., a layer in which the lowest portion is based above the earth's surface. Elevated convection often occurs when the air near the ground is relatively cool and stable, e.g., during periods of isentropic lift, when an unstable layer of air is present aloft
- A thermal column in the atmosphere – rising warm air currents (birds, butterflies and dragonflies all take advantage of rising currents to migrate)

Conduction

- Heat conduction is the process by which heat energy is transmitted through collisions between neighbouring atoms or molecules



- Flow of heat in response to a temperature gradient within an object or between objects that are in physical contact
- Particles with higher kinetic energy collide with particles with lower kinetic energy, which increases the energy of particles with lower kinetic energy and decreases the energy of particles with higher kinetic energy (warmer cools and colder heats)

Radiation

- The heat transfer by electromagnetic waves. This form of energy transfer does not require the presence of matter to occur
- In this form energy can travel through empty space from the Sun to the Earth
- Radiation also occurs within the CS between the earth's surface and the atmosphere, and within the atmosphere and ocean. Thus, the main sources of radiation are the Sun, the Earth and the atmosphere

Surface heat exchange

- horizontal and vertical temperature gradients
- heat transfer:
- radiation = heats the air directly (depending on water vapour)
- conduction = air heated (or cooled) through contact with Earth’s surface (crucial for a very thin layer of air near the surface)
- convection = warm air rises, cooler air falls (convection forced and free)
- cooling at night: radiation, conduction, convection
- during transport, part of the energy is consumed:
    - on heating,
    - phase changes,
    - changes in air volume

Specific heat: an amount of heat required to raise the temperature of a unit mass of a substance through 1°C (K)

Sensible heat: an amount of heat required to change the temperature of a substance with no phase change (associated with conduction and convection)

Latent heat: an amount of heat required to change a unit mass of a substance from one phase to another phase at the same temperature (without changing its temperature)

Heat capacity – fundamental concepts in the Climate System

- the amount of heat required to change the temperature of a given amount of matter by 1 °C (K)
- unit JK^{-1}
- ability to store heat
- for inhomogeneous surfaces (e.g., soil), it is given by the sum of individual components of the system and their percentage

Specific heat capacity

- the amount of heat needed to increase the temperature of 1 kg of substance per unit (K, °C, °F)
- unit $J^{-1} K^{-1}$
- the water has five times greater specific heat capacity than soil

For example:

- of the commonly known substances, water has the highest specific heat capacity (4.2 kJ $kg^{-1}K^{-1}$)
- the maritime climate has lower temperature amplitudes, both daily and annual, than the continental climate
- the surface layer of water heats up more slowly and cools down more slowly than the soil
- it is suitable as a coolant (car, nuclear power plants)
- water "gets more heat" than, for example, oil

- dry air =1.01 kJ kg^{-1} K^{-1}, water vapour =1.84 kJ kg^{-1} K^{-1}, wood =1.7 kJ kg^{-1} K^{-1}, sand =0.84 kg^{-1} K^{-1}
- we use more energy to increase the temperature of humid air than with dry air– humid buildings are poorly heated
- snow cover is a good insulator due to the air content (dry air insulates well)
- water has higher HC (and good conductor, high transparency)
- water requires large amounts of heat to raise its temperature, but loses and gains heat slowly
- soil, rocks, wood: Low HC

Thermal conductivity

- the ability of a substance to conduct heat
- describes the rate of heat dissipation between parts of a system with different temperatures
- unit W $m^{-1} K^{-1}$

- from a place with a lower temperature to a place with a higher temperature
- affects the subjective perception of temperature when touched

How does heating and cooling differ between these materials?
Vegetation – high reflectance
Soil – high absorption
Water – high conductance
high heat capacity
high transparency (heat transferred to deeper layers)
Dark dry soil – low conductance
high absorption
low heat capacity
opaque (concentrates heat near-surface)
Air – low conductivity
Metal – high conductivity
Poor conductors = hotter during the day and cooler at night (example – dry wood with frost)
Good conductors = moderating influence, more minor temperature change (example – lake water)

For example:

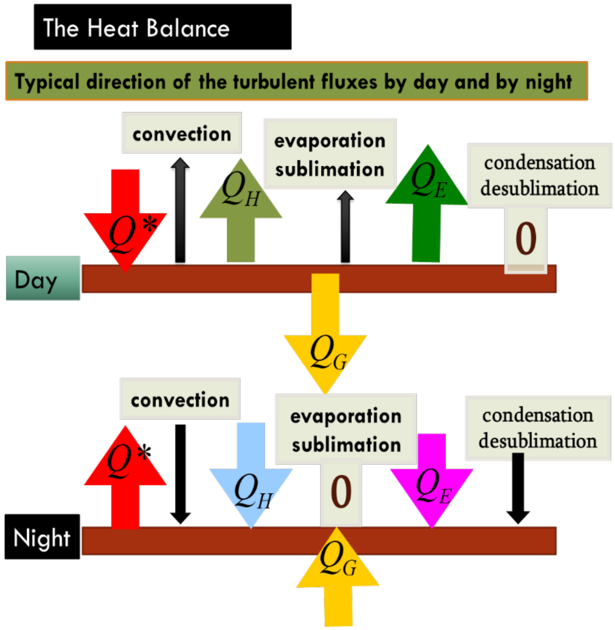
- the air saturated with water vapour has ten times higher thermal conductivity than dry air
- it depends on the amount of water and air in the soil – the moist surface does not heat up so much as dry soil
- heat removal during the night is also dependent on humidity – the moist surface does not cool down so much – heat is brought to the surface from the depths
- when the soil is moist, it more easily brings heat from the depths on the surface

4.3 Energy balance (Q*) of active surface and atmosphere

To understand how the CS balances the energy budget, we have to consider processes occurring at the three levels:

(i) the surface of the Earth, where most solar heating takes place
(ii) the edge of Earth's atmosphere, where sunlight enters the system
(iii) the atmosphere in between

The amount of incoming and outgoing energy, or net flux, must be equal at each level.
https://earthobservatory.nasa.gov/features/EnergyBalance



- After including the effects of the radiant, convective, and conductive fluxes, we can express the **energy balance** as:

$$Q^* = Q_H + Q_E + Q_G$$

Q_H – sensible heat flux

Q_E – latent heat flux

Q_G – soil heat flux

- Sum of the net shortwave and net longwave radiation receipt at the surface must be balanced by:
  - **convective loss** of energy from the surface upward - Q_H and Q_E
  - **conductive loss** downward through Q_G

- the heat balance is the result of the simultaneous action of energy flows that come to the surface (heat) and which leave the surface (cool)
- during the day, spring and summer – positive energy balance on the surface
- during the night, autumn and winter – negative energy balance on the surface
- areas closer to the equator – the heat balance is positive throughout the year
- the difference in heat balance between the oceans and the land is related to the thermal conductivity and capacity and the albedo of the surfaces
- strong dependence on latitude (angle of incidence of radiation, length of day)
- all these factors affect the value of the heat balance and the members of the balance equation:
  - Q*day = Q - R - G + A - RD - LV - KT - Qp
  - Q*night = -G + A - RD + LV + KT + Qp
- Q = direct + diffuse radiation
  - rises from the pole to the equator
  - it is not the largest in the equatorial regions, but around the 20th parallel – clouds in the Intertropical Convergence Zone (ITCZ) due to the output flow of moist air

- R = reflected solar radiation
  - dependent on the albedo of the surface
  - the water surface has a small albedo
  - much of the radiation through the water passes to greater depths
  - does not apply to frozen bodies of water
  - the land has a higher albedo than water (heat balance of the northern and southern hemispheres)

- G = surface radiation

- A = atmospheric radiation
  - absorbed by the earth's surface, but part is reflected (R_D)

- *LV = latent heat (negative value)*
  - evaporation from surfaces changes the state from liquid (solid) to gaseous
  - the heat is consumed and removed from the surface and "hidden" in water vapour

- *KT = heat transfer between surface and atmosphere by conduction, convection and turbulence*
  - the atmosphere is warming from the earth's surface

- *Qp = heat flow to or from the subsoil*
  - negative during the day (heat leaves the surface layers of the active surface to greater depths)
  - positive at night (heat from the depths reaches the surface)
- at night:
  - the Q member is missing (the sun's rays do not fall on the earth's surface)
  - -G, + A, -R_D represents the same as during the day
  - LV difference: during the night, the surface cools and water vapour does not evaporate
  - condensation or desublimation of water vapour occurs on the surface and heat is released and transferred to the surface
  - heat transfer between the surface and the atmosphere at night is positive (the surface cools faster than the atmosphere, it cools off from the surface)
  - the heat flow from the subsoil has a positive value (heat is transferred to the surface layers from greater depths)

- the heat balance on the active surface significantly affects humans
- the climate of the world is most influenced by a change in the active surface and a change in the atmosphere (Figure 4.1)

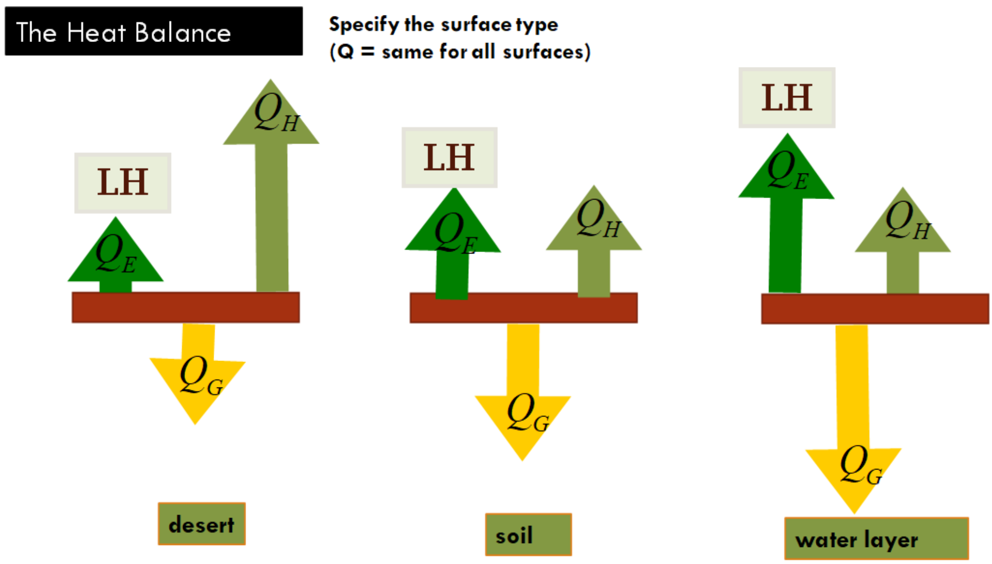


Fig. 4.1 Surface heat exchange in the desert, soil, and water layers

4.4 Comparison of the energy balance of two surfaces

1. Man-influenced landscape

- the heat balance on the active surface significantly affects by humans
- the climate of the world is most influenced by a change in the active surface and a change in the atmosphere
- landscape insufficiently supplied with water – fields, roads, paving, surface mines
- most of the incident energy is absorbed by the surface (which leads to heating of the cover)
- the minimum energy is reflected
- little energy is used for evaporation (only about 10-20 %)
- part of the energy passes to greater depths of the subsoil
- from the warm surface the air layer above it heats up – the air rises and carries heat to the higher layers of the atmosphere (possible damage to vegetation, e.g., Ore Mountains)

2. Landscape sufficiently supplied with water

- these are pond, meadow, floodplain forest
- most of the incident energy is used for evaporation (2.5 MJ per 1 kg of water)
- the energy "hides" in the water vapor
- water vapour is lighter than air, so it rises and if it reaches a height where the temperature is lower than the dew point temperature, the water condenses/desublimates and releases heat
- where it is colder, heat is released as result of natural temperature control
- the heat moves from places where there is a surplus to places where there is a shortage

Energy balance of plants

- the plants are cooled by transpiration
- part of the energy (1 %) is used for photosynthesis (a very small amount of the total power input)

Surface energy balance

- surface cooling by *transpiration* (water is part of plant tissues) or *evaporation* (evaporation of water from the soil or the surface of plants; dew, trapped precipitation; water not part of plant tissues)

Energy balance of snow cover

- affected by many factors
    - snow cover quality
    - properties of the atmosphere above the snow cover
    - presence and structure of vegetation above the snow cover (meadow vs. forest – in the forest less radiation reaches the surface, it is reflected and absorbed by the forest, in addition the trees emit long-wave radiation)
- knowledge of energy relations is important for models of water runoff during snowmelt melting and flood prediction
- the dominant component of the energy balance in winter is shortwave radiation
    - albedo is high on clear days and in tree-free locations
    - snow albedo decreases with aging or snow pollution (absorbs more radiation)
- significant energy transfer during snow sublimation or water vapour freezing (latent heat)
    - significantly affected by humidity, temperature and air velocity above the snow cover
    - rain is also an important factor (it depends on its temperature – if rain flows on the snow cover and freezes, heat is released and the probability of snow melting increases)
    - the strongest warming of the snow cover and subsequent melting occurs in relatively warm, humid air and in windy weather

    - the main source of energy for melting snow is shortwave radiation falling on the earth's surface
    - the surface absorbs long-wave radiation from the atmosphere, some of it reflects

4.5 Soil temperature

The ability of soil to conduct heat determines how fast its temperature changes during a day or between seasons. Soil temperature (ST) anomalies in the surface layers will affect short-term weather processes, while ST anomalies in deeper layers can affect regional climate processes by gradually releasing energy to shallower layers. ST is a major determinant of processes that occur in soil that are necessary for plant growth.
Example:
(i) alters the rate of organic matter decomposition and mineralization of different organic materials
(ii) affects soil water content, conductivity, and availability to plants

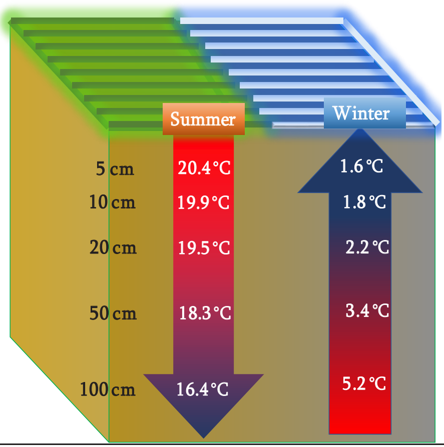
Tillage has significant effects on ST; therefore, the impact of different tillage modes and soil mulching measures on ST dynamics are commonly studied in agricultural research. Soil warming at all depths and seasons was already found to have increased. Irrigation can change the characteristics of soil temperatures that are closest to the depths of plant nodes and cause the temperature of the soil profile to be more favourable for crop development.

- Properties of the surface soil layer depend on:
  - radiation balance
  - geographical coordinates (influence on the angle of incidence of radiation)
  - clouds (absorption of sunlight and reflection of Earth's radiation back to the surface)
  - soil moisture (with increasing soil moisture its heat capacity and conductivity increase)
  - surface colour and albedo
  - exposure
  - date of sunrise and sunset
  - vegetation cover
  - snow layer
    - may have insulating properties
    - in the spring it has a negative impact – it prevents the soil from warming up and the impact of sunlight
- daily and annual course
  - the daily amplitude increases with decreasing latitude
  - the annual amplitude is small in the equatorial regions

- Fourier's laws:
  - the period of fluctuations is the same in all depths – by the period of fluctuations we mean the time between two maxima

- the amplitude of the soil temperature decreases with depth – the deviation between the minimum and maximum temperature decreases
- the onset time of maxima and minima is delayed with depth – the maximum occurs in the surface layer and, depending on the thermal conductivity, the onset of both maximum and minimum is delayed
- the fourth law describes the relationship between the depth of constant daily and annual temperature, e.g., the depth of constant annual temperature is about 19 times greater than the depth of constant daily temperature (the square root of 365 is 19)

- ST showed decreases with depth in spring and summer
- ST increased with depth in autumn and winter due to the downward temperature gradient (Fig. 4.2)



The soil temperature at five depths for each season in the period 2000–2020 for lowlands in the Czech Republic

	5 cm	10 cm	20 cm	50 cm	100 cm
spring	10.1	9.8	9.4	8.7	7.9
summer	20.4	19.9	19.5	18.3	16.4
autumn	11.1	11.2	11.5	12.3	13.3
winter	1.6	1.8	2.2	3.4	5.2

Fig. 4.2 Soil heat flux – effectively couples energy transfer processes at the surface (surface energy balance) with energy transfer processes in the soil (soil thermal regime) (Potopová et al., 2021)

4.6 Water temperature

The onset of seasons is delayed significantly over/near oceans because of the oceanic absorption of the energy through the summer and the slow release of it to the atmosphere from autumn through winter. Two of the most important characteristics of seawater are temperature and salinity – together they control its density (a major factor governing the vertical movement of ocean waters).

- the heat sources for water are
  - sunshine
  - the geothermal energy of the bottom (deep water)
  - kinetic energy (tides, movement of surface waters depending on the wind)

- radiation absorption is different compared to land
    - the radiation penetrates to greater depths
    - water has a greater heat capacity and conductivity – the water surface has a smaller thermal amplitude than the land surface
    - evaporation of water from the surface – consumption of latent heat
- average ocean surface layer 17.4 °C (atmosphere 15 °C)
- ocean water freezes at -1.9 °C during normal salinity
- the change in seawater temperature with depth is most pronounced in the tropical belt
    - the warmest water is around the equator (annual average 25–27 °C)
    - in the upper stirred layer, the temperature does not change much
    - at depths of 100–300 m there is a significant drop in water temperature with a depth of up to 4 °C (at a depth of 1000 m below the surface)
    - at the bottom of deep-sea basins, the temperature is 2-3 °C
    - around the poles, the seawater temperature is 0 to -0.5 °C
    - in Antarctica it is -2 to -3 °C (influence of salinity and water movements)
- fresh water has the highest density at 4 °C (it is a bit different with salt water)
- the daily amplitude of the water temperature in the oceans is small compared to the land temperature (highest at the equator: 0.5 °C; lowest at the poles: 0.1 °C)
- the annual amplitude of water temperature in the oceans depends on latitude
- the salt concentration is an important factor: freezing water in the seas and oceans is different from freezing fresh water
    - ice crystals form in the saltwater and a concentrated saltwater solution is between them
    - ice has a different colour and structure compared to freshwater ice
    - ocean ice can be dark to black
    - frozen areas of the ocean make up 7 % of the Earth's surface (significant effect on the radiation balance and climatic conditions of the Earth)

4.7 Air temperature

The main source of heat is the earth's surface, less so solar radiation (the atmosphere heats and cools from the earth's surface).

- heat dissipation
    - convective and turbulent flow
    - heat flow during changes of state
    - molecular conduction
    - radiation

- high vertical and horizontal variability
- dependence of daily and annual running and daily and annual amplitude on many factors:

    - insolation
    - albedo surface
    - surface radiation

Daily course of air temperature

- affected by:
    - weather (synoptic situation)
    - season
    - latitude
    - continentality of the place
    - relief of the landscape
    - surface type (presence or absence of vegetation)
- conditions in Central Europe:
    - maximum temperature in July
    - minimum in January
    - daily maximum 2-3 hours after the culmination of the sun (during the year at a similar time)
    - daily minimum just before sunrise (during the year at different times)

Annual course of air temperature

- affected by:
    - air mass regime
    - latitude
    - continentality
- comparison of climate in London and Brno
    - similar latitude
    - London – maritime climate (influenced by the Atlantic Ocean)
        - small annual amplitude
        - warmer summers, warmer winters (even though it is slightly further north)
    - Brno – continental climate
        - large annual amplitude
        - the average annual air temperature in the ground layer of the atmosphere is 15 °C
- it is significantly affected by the greenhouse effect
    - if not, the average annual air temperature would be -18 °C
- in the equatorial regions the air temperature above the land is not the highest
    - above the equator is a large proportion of clouds
    - presence of tropical forests – the evaporation of water lowers the temperature
    - temperatures are significantly higher over the Sahara, India, and the Arabian Peninsula
      (20th parallel)

4.8 Temperature gradients

- change in air temperature with altitude
- vertical geometric gradient
  - applies to the troposphere and the perpendicular profile
  - for the ground atmosphere, it is 0.65 °C per 100 m height (by 100 m higher the temperature drops on average over the whole globe by 0.65 °C)

- vertical climatic temperature gradient
  - dependent on the active surface
  - change in temperature and altitude of two places on the earth's surface
- vertical adiabatic gradient
  - the air rises, expands and cools, its relative humidity increases
  - for every 100 m in height, the saturated air is cooled by 0.65 °C (moisture-adiabatic gradient)
  - at a certain altitude, above the condensation level, the air is saturated (r = 100 %)
  - during condensation heat is released, precipitation occurs, the air dries out
  - for unsaturated air the temperature change is 1 °C per 100 m height (dry adiabatic gradient)
  - consequence: in front of the windward side in the foothills the temperature is lower than on the leeward side in the foothills

Adiabatic processes: non gain of heat / non loss of heat → when a parcel of air expands and cools, or compresses and warms, with no interchange of heat with the outside surroundings

- **adiabatic processes**

$$y = \frac{dt}{dz}$$

Dry Adiabatic Process - one in which the vertical displacement of an air parcel lead to no changes of phase

- **dry adiabatic lapse rates**

1.0°C/100 m

Moist Adiabatic Process - one in which **phase changes** in water, and the subsequent production of precipitation (e.g., snow, rain, hail, etc), occur as a parcel of air moves vertically

- **wet adiabatic lapse rates**

0.6°C/100 m

- Slow cooling due to more moisture

- under certain conditions, however, the temperature does not change with altitude (isothermia) or the air temperature increases with increasing altitude = *inversion*
  - typical of the cold season
  - the earth's surface is cooled and in the absence of convection the air does not mix
  - in cities with emissions, smog is formed
  - it can occur by radiation or advection
    - radiation origin:
      - the earth's surface cools
      - cold heavy air flows into the valley
      - the air layer above it is warmer
    - advection origin
      - advection = flow in the horizontal direction
      - warmer air slides over the colder surface
      - the transition of the warm front (warm air will rise above the cold air sector – the temperature is higher than at ground level)

4.9 Smog

- occurs under temperature inversion conditions
- *reducing smog (London, winter)*
  - it occurs during temperature inversions, when the rising flow stops and there is a small turbulent air flow
  - accumulation of substances from combustion processes (SO_2, NO_x, dust particles) – aerosol
  - thick fog with contained exhalations
  - in the Czech Republic – mainly Ostrava, northern Bohemia (high emissions of harmful substances)
- *oxidative smog (Los Angeles, summer, photochemical)*
  - it is caused by the action of sunlight on the components of traffic exhalations in the summer
  - NO_2 breaks down with radiation into NO and O radicals, which then reacts with O_2 to form O_3
  - the result is a high concentration of ozone in the ground layer
  - looks like an orange-grey layer over cities in summer
  - a big problem in the Czech Republic (ozone is toxic, undesirable in the ground layer of the atmosphere)

4.10 Climate change related to temperature

- climate change has always taken place
- there is currently an increase in temperature in the ground layer of the atmosphere and in the oceans, at the same time there is a decrease in temperature in the stratosphere (related to ozone depletion)
- the temperature change is uneven in time and space
- more pronounced warming is evident in winter
- the northern hemisphere is warming more significantly
- as the temperature of the water in the oceans increases, the solubility of the gases in the oceans decreases
- arctic summer glaciation
  - decrease globally over time
  - affects the radiation and heat balance of the active surface
  - ice has a high albedo (reflects radiation back into space)
  - the loss of ice leads to greater absorption of radiation and warming
- arctic ice is declining, but Antarctic ice is increasing
- if all the ice in the glaciers melted, the ocean level would rise by 60 meters
- floating ice in the oceans has already caused a water outflow

- melting glaciers are not currently causing ocean levels to rise
- the current rise in ocean levels is caused by the warming of water in the oceans and the related thermal expansion of the water
- large river deltas (Mekong, Nile, Niger) will be endangered by rising ocean levels
- nations are likely to migrate (people from these critical areas will move to more developed parts of the world)

4.11 Temperature versus plants

- plants have a temperature optimum for growth, development, and photosynthesis
- depends on the climate zone in which the plants developed:
    - tropical plants have an optimum in the range of 35–40 °C
    - temperate plants have an optimum in the range of 20–30 °C
    - Arctic and Alpine have an optimum in the range of 10–20 °C
- the rate of photosynthesis decreases towards lower but also higher temperatures
- with severe and prolonged thermal stress, death occurs by freezing or overheating
- plants feel stress from both low and high temperatures
- high temperature in plants causes:
    - anatomical changes
    - production of HSP (heat shock proteins)
- <u>low temperature in plants causes:</u>
    - formation of cryoprotectants (sugars, fructans)
    - formation of unsaturated fatty acids (saturated mainly tropical plants)
    - transport of water to extracellular structures (ice outside the cells)
    - THP (thermal hysteresis proteins) production

4.12 Temperature as a risk meteorological factor

cold damage to plants

- exposure to temperatures above freezing
- causes:
    - physical and physiological changes
    - disorders of enzyme and membrane lipid activity
    - slowing down photosynthesis
    - breathing acceleration
    - slowing down the intake of water and nutrients
    - stopping growth
    - disruption of the ripening process
    - premature branching of tomato stems
    - necrotic stains
    - accumulation of toxic substances in tissues (ethanol, acetaldehyde)

frost damage to plants

- exposure to sub-freezing temperatures
- causes:
  - mechanical damage to cells by the formation of ice crystals
  - changes in the physical and chemical properties of membranes in the cell
  - thickening of cell juice in vacuoles
  - disruption of metabolism
  - formation of toxins
  - watery spots
  - wilting, drying out
  - necrosis
  - frost cracks, mouldings, and boards

black frost

- frost occurs when the temperature drops below zero but the surrounding air is dry (e.g. drought conditions)
- ice can't form on the plant surface and the water between cells freezes quickly and forms large crystals
- important in relation to overwintering winter crops
- in recent years there is a short duration of snow cover (insulating effect)

ground frost

- in the spring after the awakening of vegetation
- the surface cools, cools the air layer above it
- in the higher layers the temperature may be positive, but above the earth's surface it may be negative
- dangerous for agricultural crops
- does not arise during clouds (this prevents the exit of long-wave radiation into space)
- does not form in the wind (cold ground layer mixes with the layer above it)
- does not occur when the earth's surface is sufficiently saturated with water (heat is supplied to the surface layers from deeper layers)
- does not arise under vegetation (trees are a barrier to the long-wave radiation of the earth)

late-frost event in spring

- is defined as freezing occurring after a substantial amount of warming has already accumulated, exposing emerging plant tissue to frost
- damage caused by late frosts in spring (or early frosts during fall) is a limiting factor
- the daily values of minimum air temperature ranges of 0 to -1.1 °C, -1.2 to -2.2 °C and below -2.2 °C were considered to constitute mild, moderate, and severe frost intensities, respectively
- in the future, the risk of late frosts is expected to increase as the temperature rises in the winter, which is even shorter

- spring starts earlier, but late spring frosts will occur and when the plants are already in the growing season at that time, there is a risk of damage to the plants by frost

Methods of protection of crops from damage by ground frosts

- fumigation of orchards
  - water with glycerine is injected into the flue gas of the rocket engine
  - smoke just above the earth's surface prevents the escape of long-wave radiation
- spreading plants with nonwovens
  - longwave radiation is reflected back to the surface
- direct heat sources
  - torches (paraffin candles)
  - vineyards – active heat production
- mixing air with a warmer layer over the cold
  - helicopter flight (poles over apple orchards)
  - installation of large fans
- flooding the earth's surface with an amount of water
  - the thermal conductivity of the soil increases
- fogging of orchards
  - dispersion of water droplets
  - when the ground frosts come, the water drops freeze and energy is released in the form of heat
  - when drops of water freeze on the plants, heat is released, and the plants become warm
  - in the process of melting heat is consumed (energy is then taken by sunlight)
- whitewashing tree trunks
  - delaying vegetation
  - reflection of sunlight
  - the plants later sprout and bloom
  - they have a chance to escape the period when ground frosts occur

4.13 Temperature and precipitation pattern in the Republic of Moldova

- Though the country of the RM is small (33 846 km^2), three agro-climate regions can be defined from north to south with distinguished drought climatology characteristics. The spatial distribution of the seasonal mean air temperatures and total precipitation across the territory of the RM for the reference period 1961–1990 are presented in Fig. 4.3–4.4.
- The common definition of seasons has been used: winter (December, January, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November).

- The summer mean air temperature ranges between +18.5 °C (*North agro-climatic region*) and +21.0 °C (*South agro-climatic region*), and the total precipitation between 235 mm in the north and 175 mm in the south, respectively
- The winters are relatively mild and dry, with temperatures ranging from −3.4 °C in the north to −1.4 °C in the south, and the average total precipitation is 104 mm.

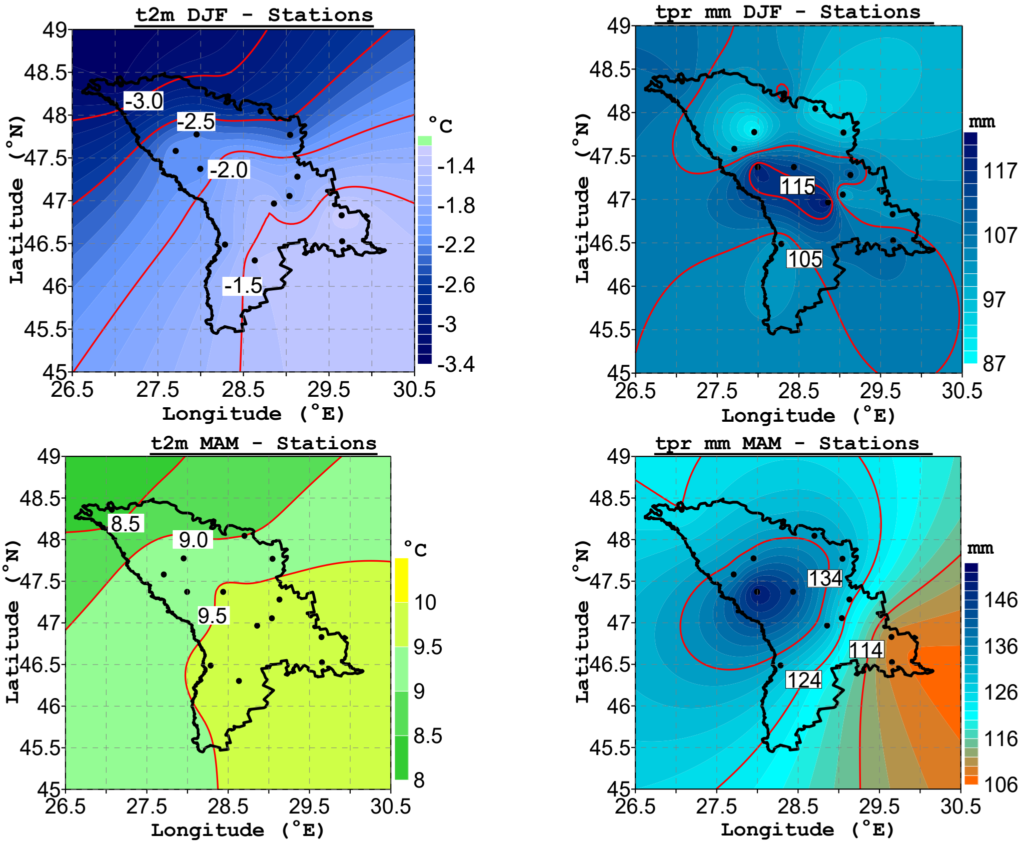


Fig. 4.3 The spatial distribution of the winter (DJF) and spring (MAM) mean air temperatures and total precipitation across the territory of the RM for the reference period 1961–1990 (Potopová *et al.,* 2016)

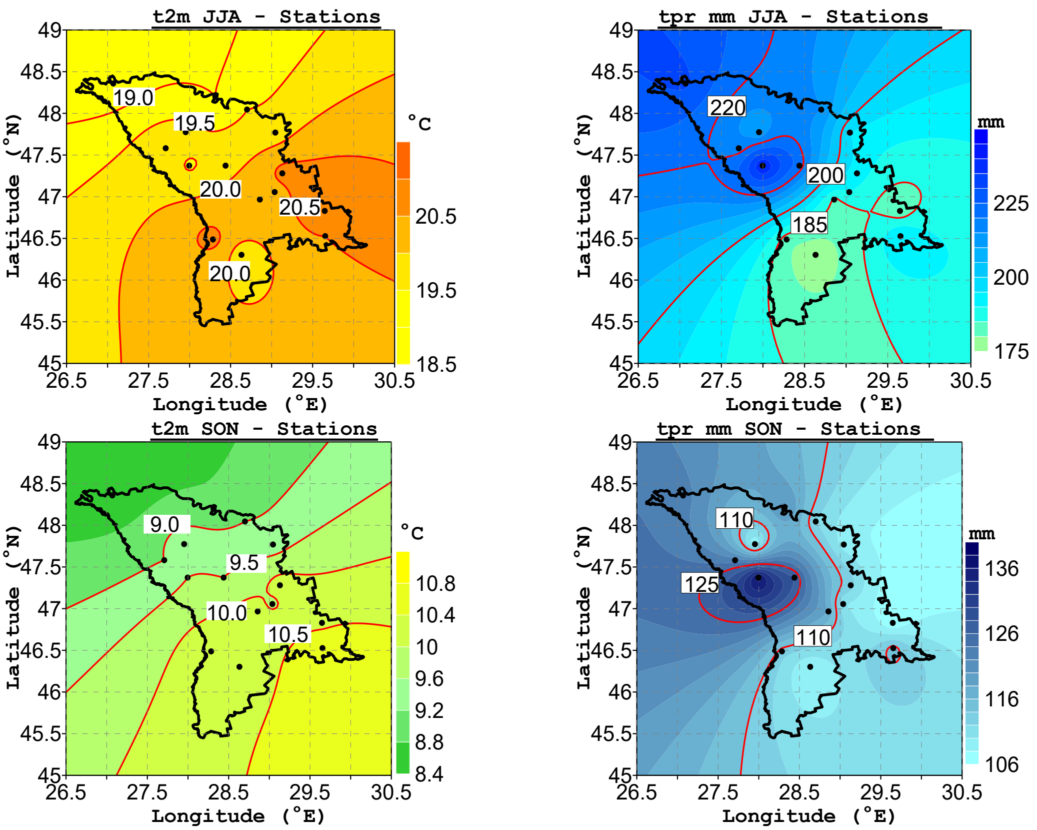


Fig. 4.4 The spatial distribution of the summer (JJA) and autumn (SON) mean air temperatures and total precipitation across the territory of the RM for the reference period 1961–1990 (Potopová *et al.,* 2016)

- The Northern agro-climatic region is characterized by optimal moisture conditions for growing cereals, sugar beet, sunflower, tobacco, and fruit trees.
- It has the shortest frost-free period lasting 178–188 days, and the highest amount of annual precipitation. The annual mean air temperature ranges from 6.3 to 9.7 °C and the mean annual precipitation amount varies from 520 to 680 mm.
- The accumulated temperature above 10.0 °C is 2750–3100 °C and lasts around 175–182 days.
- The Central agro-climatic region ensures more accumulated heat ranging between 3000 and 3300 °C with an average annual duration of 182–187 days, which represents optimal agro-climatic conditions for growing cereals, fruit trees, and grapevines.
- The annual mean temperature ranges from 7.5 °C to 10.0 °C and the average annual precipitation total varies from 520 to 660 mm.
- The Southern agro-climatic region is characterized by the highest accumulated temperature above 10.0 °C ranging 3200-3400 °C with an average annual duration of 180–190 days.

- ✧ The annual mean air temperature ranges from 8.3 °C to 11.5 °C and the average annual precipitation total varies from 490 to 550 mm.
- ✧ The climatic conditions ensure the longest growing season and the longest frost-free period lasting 181–190 days per year.
- ✧ Precipitation is not evenly distributed during the year. Summer is the wettest season, with precipitation totals contributing 39% to the annual total. Conversely, winter is the driest season, accounting only for about 17% of the annual precipitation total, followed by fall and spring.

Ch4 Sources:

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  Video Microsoft Stream

Additional sources:

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Chapter 5

Evapotranspiration in energy translocation, condensation products, and their impact on ecosystems

Keywords:

- crop water balance
- evaporation
- transpiration
- evapotranspiration
- real & potential evaporation
- condensation and desublimation products
- virtual water
- water footprint
- green water

Chapter 5: Evapotranspiration in energy translocation, condensation products, and their impact on ecosystems

5.1 A schematic of the hydrological cycle of the earth system

The water cycle is the continuous circulation of water in the Earth-atmosphere system. Although the total amount of water within the cycle remains essentially constant, its distribution among the various processes is continually changing. The most important processes involved in the water cycle are evaporation, transpiration, interception, infiltration, percolation, condensation, precipitation (rainfall, snowfall, hail, sleet, fog, dew, drizzle, etc.) and runoff (surface runoff, interflow, and baseflow).

Water on Earth

- earth's surface $\Rightarrow$ 510 million km^2, of which 361 million km^2 are oceans and seas (70.8%)
- uneven water distribution
  - northern hemisphere 155 million km^2 (43 %)
  - southern hemisphere 206 million km^2 (57 %)

- this inequality significantly affects the hydrological cycle and climate formation (great influence on the radiation and heat balance of the northern and southern hemispheres)
- salt water 97 % and freshwater 3 %
- freshwater:
    - ice sheets and glaciers 68.3 %
    - groundwater 31.4 %
    - other sources 0.04 %
    - surface water 0.03 %
- surface water:
    - lakes 87%
    - swamps and marshes 11%
    - river 2%

The phases of the hydrological cycle are following:

- transport of water
- temporary storage
- change of state:
    - evaporation – energy consumption (2.5 MJ per 1 kg H_2O)
    - condensation – energy release (2.5 MJ per 1 kg H_2O)
    - melting – energy consumption (0.334 MJ per 1 kg H_2O)
    - solidification – energy release (0.334 MJ per 1 kg H_2O)
    - sublimation – energy consumption (2.834 MJ per 1 kg H_2O)
    - desublimation – energy release (2.834 MJ per 1 kg H_2O)

- Evaporation from the Earth's surface is 577,000 km^3 per year:
    - from the oceans 505,000 km^3
    - from land 72,000 km^3

The water cycle

- 496,000 km^3 of water evaporates from the land/ocean surface annually, remaining for about 10 days in the atmosphere before falling as rain/snow
- the amount of solar radiaton necessary to evaporate this water is half of the total solar radiation received at Earth's surface
- one-third of the precipitation falling on land runs off to the oceans primarily in rivers, while direct groundwater discharge to the ocean accounts for only about 0.6 % of the total discharge
- a small amount of precipitation is temporarily stored in the waters of rivers/lakes
- the remaining precipitation over land, 73,000 km^3 per year, returns to the atmosphere by evaporation

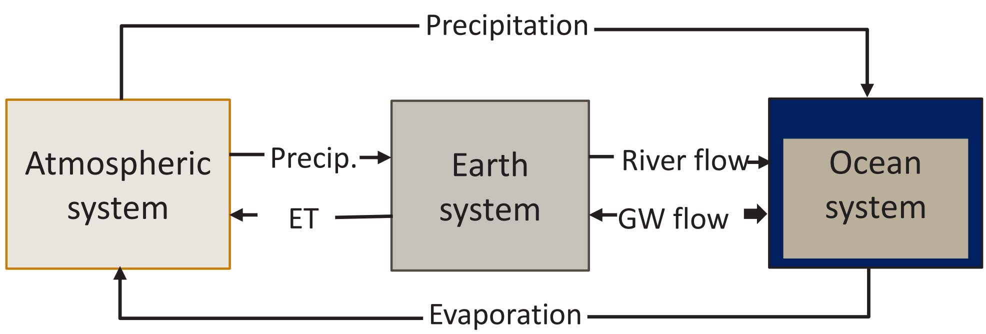
- over the oceans, evaporation is higher, and the net difference represents the transportation of water vapour over land, where it precipitates as rain/snow and returns to the oceans as river runoff and direct groundwater discharge

Water in the atmosphere

- in the atmosphere, approx. 13,000 km^3 of water vapour is stably bound
- of these, 75 % are above the world's ocean level and 25 % above land
- areas with the maximum of this moisture are located
  - in the equatorial and tropical belt of the western Pacific Ocean
  - in the Amazon River basin
  - in the north-eastern part of South America
- monsoons and trade winds – a large amount of precipitation over the mainland and large runoff
- the position of the intertropical convergent zone corresponds to the thermal equator

Changes over time

- the residence times of a reservoir within the hydrologic cycle is the average time a water molecule will spend in that reservoir



ET – evapotranspiration; GW – ground water

Fig. 5.1 A schematic of the hydrological cycle of the earth system

Vapour

- thanks to its kinetic energy, the water molecule overcomes the cohesive force of the liquid and flies into the air
- vapour – molecules that have left the liquid minus molecules that have returned to the liquid
- dependents on
  - temperature

   - humidity (saturation supplement)
   - wind speed
   - type of active surface
   - surface colour (albedo + surface temperature)
   - surface moisture (how much water is available)
   - type and age of vegetation
   - salinity (sea and oceans)
- the warmer the water, the easier it will be for the molecules to leave the liquid
- warm air holds more water vapour than cold air
- there is a layer of air above the evaporating environment – the wind carries away a layer of air and air with a higher saturation supplement it's formation

5.2 Concepts related to evaporation

- ☞ The oceans, seas, lakes, and rivers provide 90 % of the moisture in the atmosphere via evaporation, with the remaining 10 % being contributed by plant transpiration.
- ☞ The terms potential evaporation and potential evapotranspiration are to be differentiated.

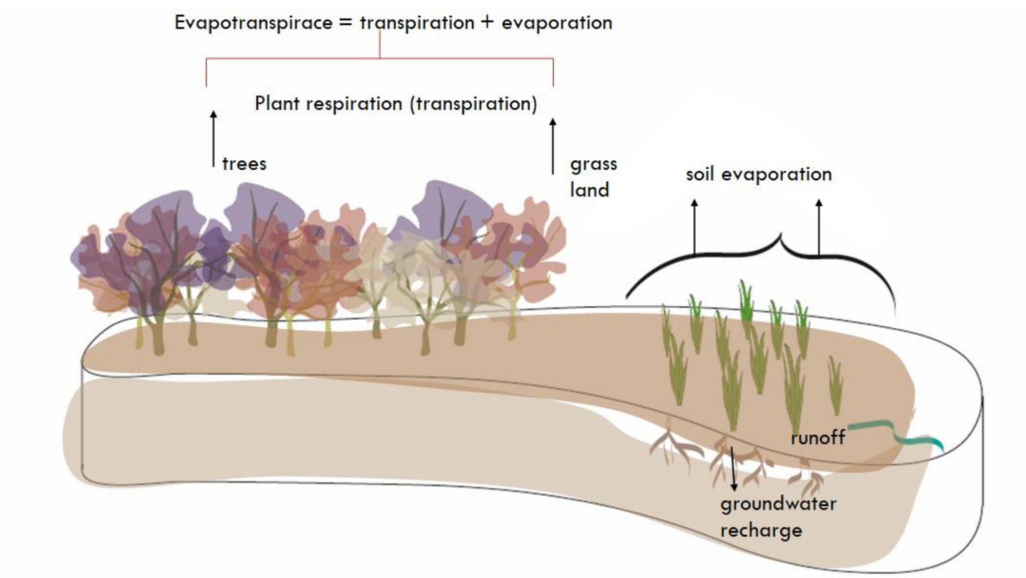


Fig. 5.2 A schematic proses of evapotranspiration as an important part of the water balance (water cycle)

Definition

Free-water evaporation ☞ evaporation that would occur from an open-water surface in the absence of advection and changes in heat storage

Evapotranspiration (ET)☞ the sum of plant transpiration and evaporation

Evaporation ☞ net loss of water from a surface resulting from a change in the state of water from liquid to vapour and the net transfer of this vapour to the atmosphere

- accounts for the movement of water to the air from sources such as the soil, canopy interception and water bodies
-

Transpiration ☞ evaporation of water from the vascular system of plants into the atmosphere

- the process involving water loss from plants
- vaporization occurs in intercellular spaces of the plant tissue, while exchange with the atmosphere occurs through and is controlled by plant stomata

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes.

We can distinguish three aspects of evapotranspiration:

- potential evapotranspiration (PET)
- actual evapotranspiration (ET_a),
- reference evapotranspiration (ET_o)

PET – the amount of evaporation that would occur if a sufficient water source were available

ET_a – the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration

✓ the water lost under real conditions.

✓ ET_a < PET {except where the surface is continuously moist}

ET_o – the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, the bulk surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, and no moisture stress.

<u>Units</u>

- ET rate is normally expressed in mm per unit time
- time unit can be in hour, day, decade, month or even an entire growing period or year
- rate expresses the amount of water lost from a cropped surface in units of water depth
- water depths can also be expressed in terms of energy received per unit area
    - ⇨ the heat required to vaporize free water

  - ⇨ this energy, known as the latent heat of vaporization (λ) ☞ λ = 2.45 MJ kg^{-1} ⇨ 2.45 MJ is needed to vaporize 1 kg
- an energy input of 2.45 MJ per m^2 can vaporize 1 mm of water
  - ⇨ 1mm of water is equivalent to 2.45 MJ m^{-2}
    - ☞ ET rate expressed in units of MJm^{-2}day^{-1}

<u>ET processes</u>

For the process of evapotranspiration, three basic physical requirements in the soil-plant-atmosphere system must be met:

- continuous supply of water
- energy to change liquid water into vapour
- vapour pressure gradient (E-e) between the evaporating surface and the air

✋ ET is an energy-controlled process requiring the conversion of available radiation energy and sensible energy (*H* - heat contained in the air) into latent energy (λ - energy stored in water vapour molecules).

<u>Classification of ET processes</u>

- Surface type:
  - ✓ open water
  - ✓ bare soil
  - ✓ leaf/canopy type
  - ✓ crop type
  - ✓ land region
- Water availability
  - ✓ unlimited vs. limited
- stored energy use
- water-advected energy

often assumed negligible

<u>Factors affecting Evapotranspiration</u>

- <u>Weather:</u>
  - solar radiation
  - air temperature
  - relative humidity
  - wind speed
- <u>Crop characteristics:</u>
  - crop type and variety (height, stomatal control, reflectivity, ground cover, etc.)
  - stage of development
- <u>Management:</u>
  - irrigation management
  - irrigation method

- cultivation practices
- fertility management
- disease, and pest control

- Environmental conditions:
    - soil type, texture, and water-holding capacity
    - soil salinity
    - soil depth, and layering
    - poor soil fertility

5.3 Methods and models review

- the first vapour flux measurements were initiated by Thornthwaite and Holzman in the 1930s, but their work was interrupted by World War II
- in the late 1940s Penman (1948) published the paper "Natural Evaporation from Open Water, Bare Soil and Grass" in which he combined a thermodynamic equation for the surface heat balance and an aerodynamic equation for vapour transfer
- the "Penman equation" is one of the most widely used equations in the world
- the equation was later modified by Monteith (1965; 1981) and is widely known as the "The Penman-Monteith Model"
- it is also necessary to introduce a review of the work of Bowen, who in 1926 published the relationship between the sensible and latent heat fluxes, which is known as the "Bowen ratio"
- measurement of the water vapour flux became a common practice by means of the "Bowen ratio energy balance method" (Tanner, 1960)

Measuring evapotranspiration

- the measurement of ET is difficult
- several systems of measurement have been developed:

(1) direct measurement
(2) meteorological formulae
(3) moisture budget methods

Estimating ET_a, ET_o and PET by meteorological formula methods can be grouped into five categories:

(1) water budget
(2) mass-transfer
(3) combination
(4) radiation
(5) temperature-based

☝ Food and Agriculture Organization of the United Nations (FAO) and American Society of Civil Engineers (ASCE) have adopted the Penman-Monteith method as the standard for computing ET from climate data.

Direct measurement

"Potential evaporation"

Evaporimeter, mm

$$E_{pan} = W - (V_2 - V_1)$$

where

W = precipitation during time Δt

V_1 = storage at beginning of period Δt

V_2 = storage at end of period Δt

☞ The rate at which the water is lost through evaporation is measured with an **evaporimeter**.

☞ This procedure measures only potential evaporation.

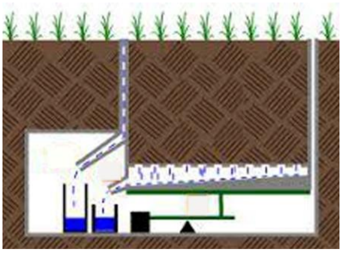
Date	Evaporation, mm	rainfall, mm	r (%)
05/27/2014	+ 148.3	35.7	92.8
05/28/2014	+168.6	10.0	94.3
05/29/2014	+76.2	3.4	93.2
05/30/2014	+7.6	0.3	78.6
05/31/2014	-32.8	0.0	63.4
06/01/2014	-45.0	0.0	57.2

📖 The word ‘lysimeter’ is derived from the Greek root ‘lysis’ which means movement, and ‘metron’ which means to measure

- Lysimeters:
  - ✓ difficult and expensive to construct
  - ✓ require careful operation and maintenance
  - ✓ primarily research application
  - ✓ primary tool for evaluating weather effects on ET and evaluation of estimating methods

✍ regular weighing allows the moisture content to be determined

✍ if the amount of precipitation is known, the moisture loss through ET can be calculated



✍ Lysimeters are tanks filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evaporation and transpiration.

The importance of evapotranspiration in energy transport

- in the Czech Republic up to 25 mJ of solar energy (6 kWh) per day per 1 m^2
- maximum flow on a summer sunny day is up to 1000 W $m^{-2} \Rightarrow$ 1000 MW/100 ha (1 km^2) the output of one unit of Temelín NPP is 1055 MW
- area of the Czech Republic – 78,866 km^2 (78,866,000 MW from the Sun; installed capacity of all power plants 22,000 MW)
- on a summer day, 3 to 5 litres of water evaporate from 1 m^2
- the heat of vaporization is 2.5 MJ per litre of $H_2O \Rightarrow$ 7.5 – 12.5 MJ m^{-2}/day
- if water is not available, the Sun's energy falling on the surface will turn into heat
- energy falling on 100 ha (1 km^2) corresponds to the perfect combustion of 750 tons of coal
- by evaporation under energy, it is stored in water vapour and released where it is colder (condensation) – thermoregulation of ecosystems (Fig. 5.3)

Which of the air conditioners will have more power?

Air conditioning

- the average cooling capacity of the most expensive air conditioning is 6 kW
- the air conditioning unit outside releases heat outside the building

<u>Tree</u>

- evaporation 400 l of water per day
- transposes about 10 hours
- 2.5 MJ of energy is needed to evaporate each litre

- it is 0.7 kWh/l of water, it makes 280 kWh/10 h
- the average cooling capacity of the tree is 28 kW

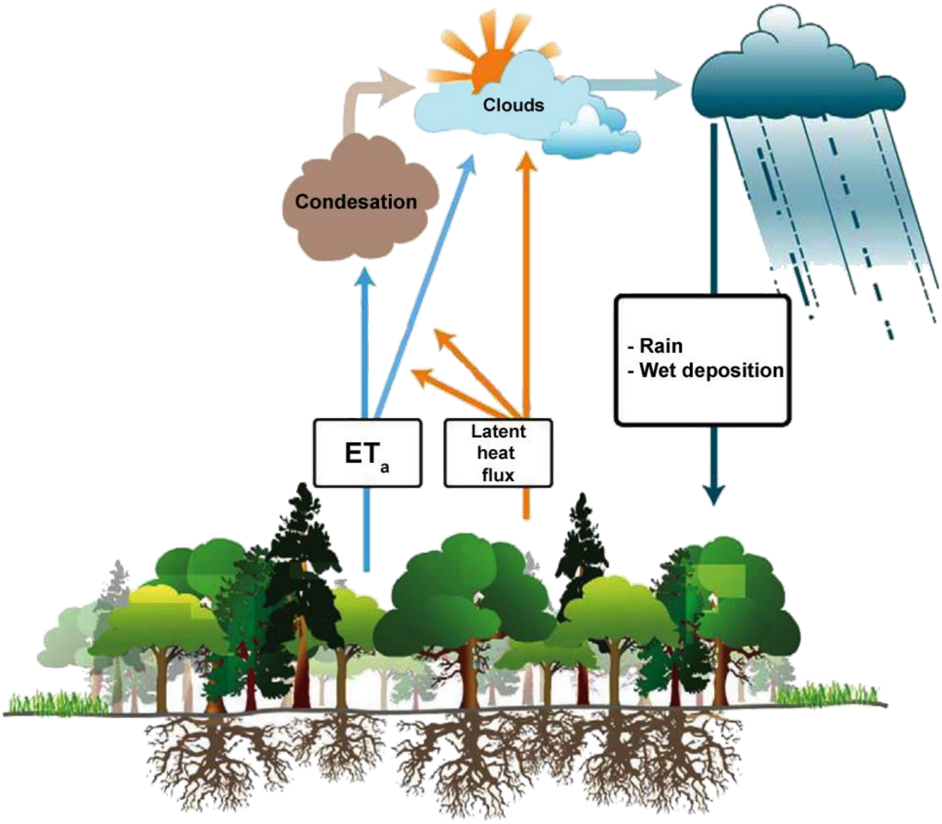


Fig. 5.3 Energy translocation through evapotranspiration in ecosystem

Source: Modified after Image courtesy of the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) user facility

5.4 Geographical patterns of evapotranspiration

- ❖ varies with latitude, season, time of day, and cloud cover
- ❖ maximum under the clear skies and long hot days of tropical areas
- ❖ minimum in the cold, cloudy polar regions

❖ temperatures are more constant in tropical regions
  - ❖ but large seasonal differences in precipitation (monsoon cycles) ☞ are the main cause of variations in the availability of water
  - ❖ most of the ET of water occurs in the subtropical oceans
    - ❖ high quantities of solar radiation provide the energy required to convert liquid water into a gas

❖ there is considerable variation in E (evaporation) and P (precipitation) over the globe

- in order for P to occur, there must be sufficient atmospheric water vapour and enough rising air to carry the vapour to an altitude where it can condense and precipitate
- P and E vary with latitude and their relation to the global wind belts
- the trade winds are initially cool, but they warm up as they blow toward the Equator
- these winds pick up moisture from the ocean, increasing ocean surface salinity and causing seawater at the surface to sink
- when the trade winds reach the Equator, they rise, and the water vapour in them condenses and forms clouds
- net P is high near the Equator and also in the belts of the prevailing westerlies, where there is frequent storm activity
- E exceeds precipitation in the subtropics, where the air is stable, and near the poles, where the air is both stable and has a low water vapour content because of the cold
- the Greenland Ice Sheet and the Antarctic Ice Sheet formed because the very low E rates at the poles resulted in P exceeding E in these local regions

5.5 Quantification of crop water balance under irrigated areas

- Crop water balance:

To calculate the crop water balance (WB), the following equation was used:

$WB = Rain - ET_a$

Rain – amount of daily precipitation
ET_a – values of actual evapotranspiration

To determine the period of the highest crop water consumption, ET_a can be expressed as follows:

$ET_a = ET_a1 + ET_a2$
$ET_a1 = ET_o \cdot K_c \cdot K_s1 \cdot Ratio1$
$ET_a2 = ET_o \cdot K_c \cdot K_s2 \cdot Ratio2$

ET_a1 and ET_a2 – the values of actual evapotranspiration from the top layer and rootzone layer
ET_o – the value of reference evapotranspiration
K_c – the coefficient describing the properties of the crop canopy and its phenological
K_s – the soil water stress coefficient
Ratio1 and Ratio2 – the shares of water absorption from the topsoil and subsoil layers

The crop coefficient K_c was formulated by the following equation:

$$K_c = K_{c(tab)} + [0.04\,(u_2 - 2) - 0.004\,(RH_{min} - 45)]\,(\frac{h}{3})^{0.3}$$

$K_{c(tab)}$ – value of $K_{c,ini}$, $K_{c,mid}$ or $K_{c,end}$;
RH_{min} – mean daily minimum relative humidity (%) for both mid-season
h – mean crop height (m) during the growing stages

5.6 Humidity and orography

- the amount of water vapour held in the air
- water vapour is an integral part of the air
  - performs two major functions:
    - (1) its presence keeps the planetary surface warmer
    - (2) it is the principal phase of the ascending part of the water cycle
- the troposphere contains 99% of water vapour,
  - with 50 % of the total content in the atmosphere located at a height of 1.5 km
- in natural conditions the air always contains a certain amount of water vapour = dry air does not exist
- air at a given temperature, can contain only a maximum amount of water vapour – air saturated with water vapour
- the amount of water vapour in the saturated air at constant atmospheric pressure is a function of the temperature
- creates the equilibrium between the phases of water (saturation)
- SUPERSATURATION ⇒ imbalance, leading to condensation (water vapour turns into water such as dew formation) and deposition (also known as desublimation – water vapour turns as ice)
- water vapour to dew – water vapour turns from a gas into a liquid, such as dew on the morning grass
- water vapour transforms directly into ice, a process that often occurs on windows during the winter months
- saturation – air that contains as much water vapour as possible (at a given temperature) such that additional water vapour would result in condensation
- unsaturated – air that contains less water vapour (at a given temperature) than possible
- supersaturation – air that contains more water vapour than possible (at a given temperature)

For example:

- if we evaporate water in a closed container, eventually the evaporated water vapor will condense back into the liquid
- the air above the water is said to be saturated with water vapour when the evaporation and condensation rates reach equilibrium

• humidity decreases rapidly with increasing altitude, and obstacles to airflow can trap large amounts of air humidity
• the air rises - it cools down - its temperature decreases and the amount of water vapour that can occur in the air - condensation of water vapour
• **föhn** - type of wind related to orography (Fig. 5.4)

- ✓ as air rises, it cools by 1°C per hundred meters until the condensation level is reached
- ✓ above the condensation level it cools below the dew point temperature
- ✓ then the air temperature drops by 0.6°C per 100 metres, precipitation occurs and the humidity decreases
- ✓ on the leeward side the air drops down and heats up by 1°C per hundred metres
- ✓ also manifests itself in the Czech Republic
  e.g., Šumava (more thermophilic vegetation on the leeward side), Ore Mountains (rain shadow), South Moravia (leeward side of the Alps)

Influence of humidity on living organisms

• recommended values of relative humidity for living rooms 30–70%
• high humidity → high thermal conductivity of air, higher heat capacity
• at higher temperatures reduces evaporation and thus reduces cooling
• at low temperatures supports heat conduction and thus increases cooling
• low humidity supports the multiplication of microorganisms, increased dustiness (problem of stable microclimate) on the drying of mucous membranes that lose their protective function (mucus barrier)

The effect of reducing the humidity around the plant

• increase in peristomatic transpiration

- ✓ on reducing the tension of the vent clamping cells
- ✓ on closing vents (the plant is hungry - it does not receive CO_2)

• increased transpiration

- ✓ on reducing the water potential of leaves
- ✓ closing vents Influence of high humidity around the plant

Influence of high humidity around the plant

• plants do not form a cuticle (in vitro plant propagation, greenhouses)
• development of fungal diseases - cracking of tissues (cherries)
• important during storage
  ✓ by most crops 90-95 %
  ✓ salads, stems, root cabbage 95-100 %
  ✓ onions and garlic 65-75 %
• some plant species require high humidity (e.g., epiphytes)

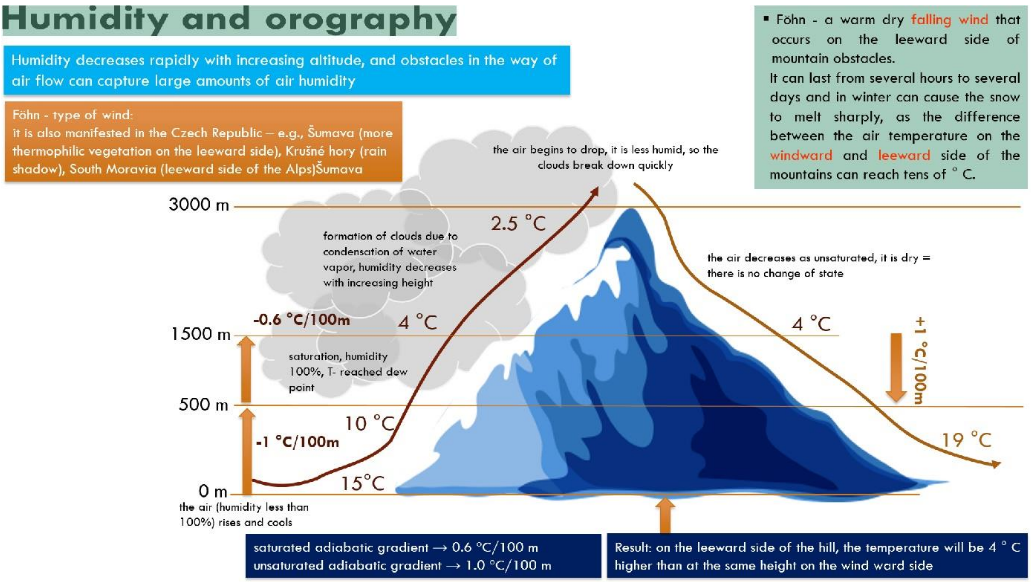


Fig. 5.4 A schematic proses of type of wind related to orography

5.7 Climate change and water balance

- change in water balance is the difference between precipitation and reference ET according to climate models
- all models predict a negative water balance (drought risk)

Aral Sea

- imbalances and changes in the water balance
- lies between Kazakhstan and Uzbekistan
- originally the 4th largest inland lake in the world, it was slightly smaller than the Czech Republic, the depth was 68 m
- tributaries of the Amu Darya and Syr Darya

- megalomaniac Soviet irrigation plan implemented in the 1950s caused the lake to dry out (due to irrigation of cotton plantations)
- in the form of precipitation, the evaporated water fell in other river basins
- the lake level began to drop
    - thickening of the salt solution (the water in the lake is getting more saltier)
    - all life died
    - heat capacity decreases (heats up and cools down faster)
    - water served as an important climate regulator (warmer in winter, colder in summer)
    - climate change in the area: between 1960 and 2000, the average summer air temperature around the lake increased by 2-6 °C and winters cooled
    - decrease in precipitation and further drying
- today the salt desert
- poisonous salt dust is blown away by the wind (rivers passed through the agricultural landscape and a large number of pesticides were removed through them), which annoys the surroundings of the lake
- the lake cannot be saved
- today attempts to protect the northern part of the lake, which is separated by a strait from the rest

Drainless areas

- territory not belonging to the basin of any ocean
- makes up about 21.5% of the mainland
- the largest continuous landlocked area in the world are following:
    - Central Eurasia
    - Sahara region
    - Arabian Peninsula
    - Central Australia
    - Kalahari Desert
    - Central Andes
- the largest stagnant river is the Volga flowing into the Caspian Sea

Drainage areas

- they have hydrological connections with the world's oceans
- makes up about 78.5% of the mainland
- runoff from land to oceans 47,000 km^3

Retention ability of the landscape

- adjustment of human flow
  - settlement of river flows
  - concreting of riverbeds
- retention capacity significantly lower than in the natural stream around which there are floodplains and floodplain forests
- the retention capacity of the Austrian landscape is better than in the Czech Republic - given the structure of the landscape

5.8 The landscape without water does not work

- water retention in the landscape ⇒ anti-drainage treatments (limits, infiltration ditches, ploughing method) = landscape revitalization
- soil needs organic matter, not only has a production function, but also maintains a hydrological cycle
- the wetter the soil, the more water it absorbs (soil retains 10 times more water than dams)
- trees are compared to air conditioning units – while they have a power in the order of kilowatts, each tree is cooled by a power of tens of kilowatts
- on the contrary, the water level is similar to the air conditioning unit
  - the worst in terms of water evaporation is then a field without crops, but often with them
- unlike forests, which are able to evaporate a lot, agrosystems in the form of fields with crops that we grow for our livelihood usually evaporate as much or less than evaporation from the free water surface
- this means that the larger the area of agricultural land and at the same time the longer the land remains uncovered during the year, the more it acts as a radiator that dries and warms the landscape

Water in the landscape has a significant impact on climate change mitigation/intensification

- landscape air conditioning function (vegetation)
- apparent heat of approx. 56,000 GWh will be released (annual production of all power plants in the Czech Republic) + water requirements (underground/surface) ⇒ "when there is no water, it is hotter – soil water is like human sweat"
- the amount of apparent heat released from the 20 km ^{2} dewatered surface corresponds approximately to the installed capacity of coal-fired power plants in the Czech Republic (12,000 MW)

Intensive water management in the Czech Republic

- 1,081,836 ha (25.4 %) of agricultural land was drained
- 72.2 % of agricultural land ploughed
- 36,527 km (40.2 %) of watercourses were modified

- a significant area was "covered" in front of the water by construction activities = rainwater drainage

Water in the landscape

- with the loss of 20 million tons of topsoil per year, the ability to retain water in the volume of approximately 6 million m^3 per year will disappear
- in 1918, a third of river flows were regulated and there were 17 dams in the Czech Republic
- at present, more than 90 % of domestic flows are regulated and there are around 180 dams
- nevertheless, even this massive man-made change in water regime did not prevent drought, did not retain water in the landscape or save agricultural production
- the total length of watercourses in the Czech Republic was reduced by a third due to regulations, in some rivers even by two thirds (thanks to the reconstruction of naturally meandering streams lined by floodplains into upright canals surrounded by flood defences and drained landscape)
- well-managed land could hold up to 40 % more water than now (up to 8.4 billion m^3 of water), a volume incomparable to any technical solution, such as dams

5.9 Water footprint - the concept of virtual water

- water footprint – the total volume of fresh water needed to produce goods and services that are consumed by a given social unit
- the water footprint thus consists of two parts: the consumption of domestic and foreign water resources
- rainwater can be divided into green and blue water:
    - ➢ green water is part of the precipitation that gets back into the atmosphere evapotranspiration (evaporation and transpiration covers)
    - green water is the only source of water in agriculture that is fully dependent on rainfall
    - ➢ blue water is the surface and underground water which is consumed during the production cycle of a product or service. In the case of crop production, it is therefore the water used for irrigation from irrigation tanks or ponds
- the water footprint of an agricultural or industrial product or service contains a total of three components: green, blue and gray water
    - ➢ gray water e.g., water, which is contaminated during the manufacturing process
        - ✓ it is defined as the volume of water needed to dilute the pollution discharged into natural waters so that the resulting concentration of water pollution remains below the legal limits of the state

5.10 Drought climatology in the Republic of Moldova

Prolonged high positive temperature anomalies associated with below-normal rainfall during the spring and summer of 2018 have turned formerly green fields into dusty, dying patches of soil across Europe Farmers are facing crop failure, and insurance companies estimate the damage to be as high as more than 210 million euros. Interestingly, in Central Europe, the persistent drought period during 2014–2019 affected different regions during different times of the year. Conversely, the countries in south-eastern Europe were less affected by drought; however, the prevailing wet period during 2016–2019 was not nearly enough.

During the last 15–20 years droughts increased in intensity and persistence compared to the past in the RM, mostly due to increased temperatures and decreased precipitation in the region. Drought and heat stress often occur simultaneously (e.g., 1994, 2007, and 2012 in the Central and South agro-climatic regions of Moldova), but they can have different effects on various physiological, growth, developmental, and yield forming processes (Fig. 5.5-5.6).

The driest month of 2012 was June, followed by August, and July, while moderate drought in April and September was detected at 47% of the stations. The development of extreme drought in 2012 was mainly attributed to:

(1) unprecedented increased temperature (up to 2.5 °C higher than average) and precipitation deficit (up to 50%) lasting from August to November 2011 and affecting 80% of the country
(2) high positive summer temperature anomalies in 2012 (more than 2.5 °C) associated with below normal rainfall (less than 39% of the normal)

- ✧ The main persistent dry periods identified in all regions were 1951–1955, 1990–1994, and 2000–2012, while the prevailing wet persistent periods were during 1968–1974, 1977–1982, 1996–1997, and 2008–2010
- ✧ The wettest periods in the RM were associated with the coldest decade 1971–1980, which coincided with that reported for Southern and Central Europe, while the driest periods were associated with the warmest decade 2001–2010, which was reported as the warmest at a global scale
- ✧ Drought is one of the limiting factors of crop yields with respect to the climate conditions in Moldova
- ✧ Drought during the plant reproductive stages may significantly reduce grain yield potential
- ✧ During the growing season of maize and sunflower, the potential evapotranspiration (PET) exceeds the amount of precipitation by 300 mm in the north and more than 400 mm in the south. This may translate into much greater yield variability at the farm level
- ✧ Short-term heat stress, hailstones, the last spring frost, and winter frost, can also influence crop management
- ✧ Hailstorms are often catastrophic; that is, areas with damaged crops reach thousands of hectares with 50–100% damage rates

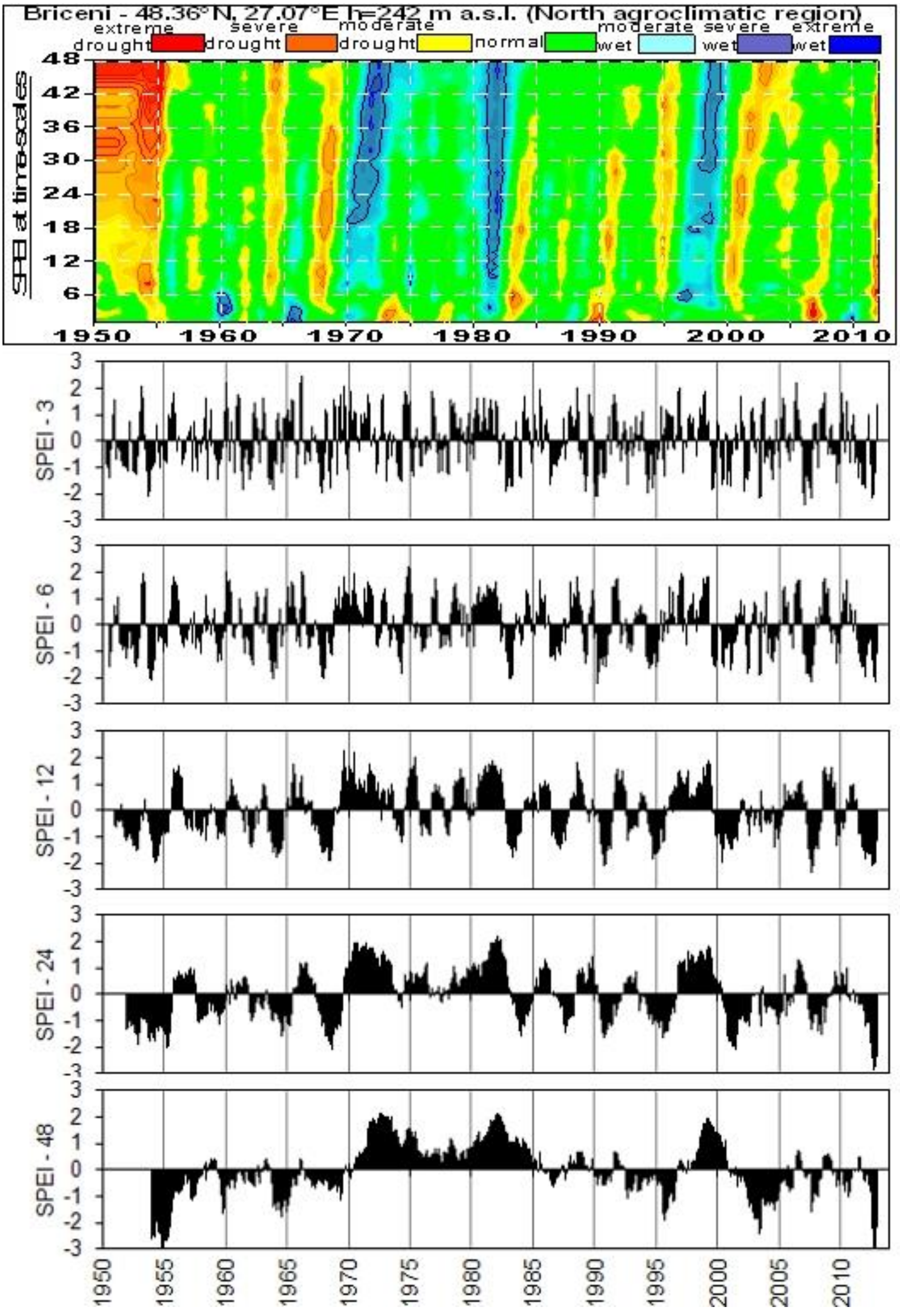


Fig. 5.5 Spatiotemporal variability of drought and wet events in the north agro-climatic region

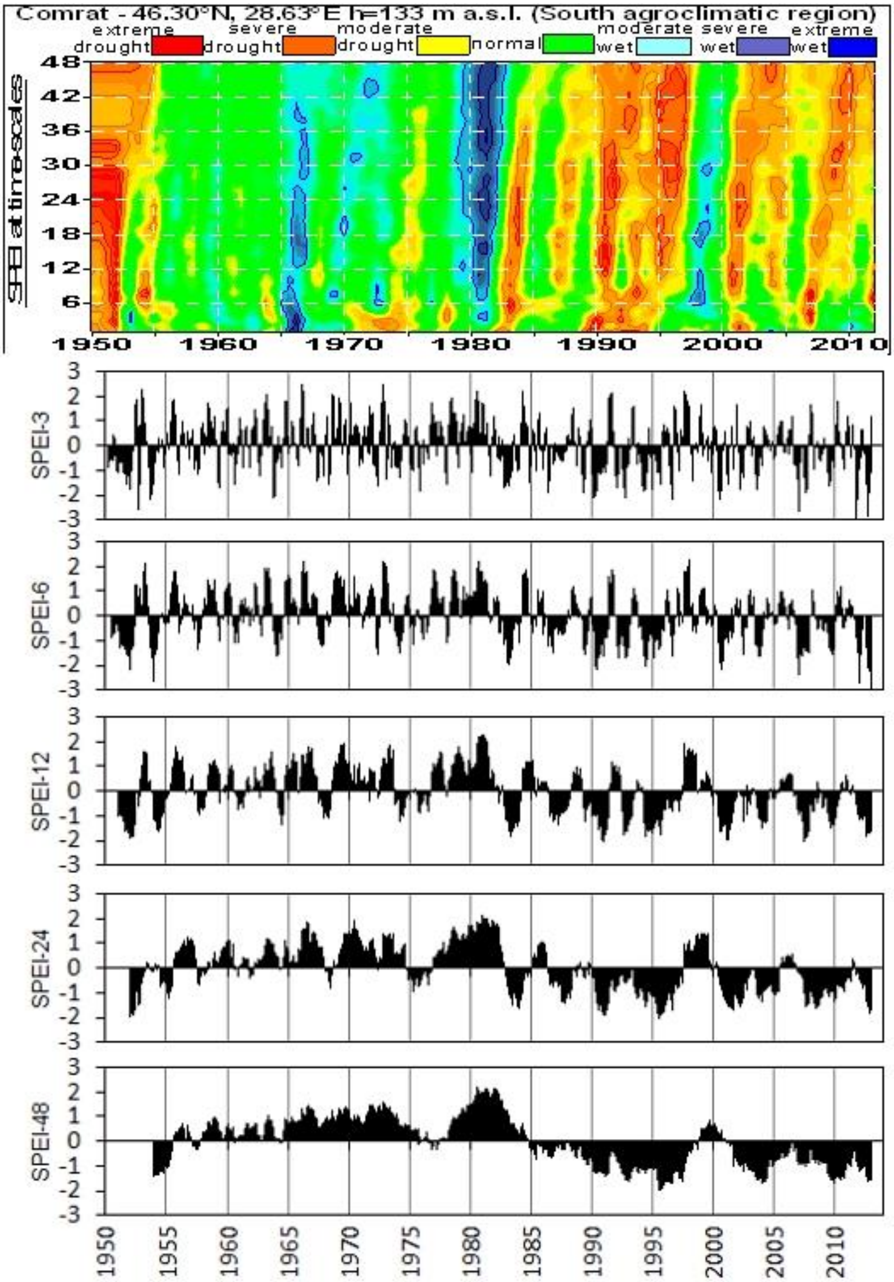


Fig. 5.6 Spatiotemporal variability of drought and wet events in the south agro-climatic region

Drought impact

- ✧ Moldova is one of the most productive agricultural regions and can be a major supplier of agricultural products because of its chernozem soil (80 %) and the fact that it has the highest accumulated temperature above 10.0 °C and the longest growing season and frost-free period
- ✧ Field crops and perennial plantations play an important role in the economy of the country, and crop yield is a key element of rural development and an indicator of national food security
- ✧ Grain maize represents the most prevalent summer crop, making up approximately 35–40 % of the structure of cereals in the study region
- ✧ Sunflower is the most important oilseed crop (vegetable cooking oil and sunflower meal), with a total sowing area of 17.3 %
- ✧ Viticulture includes a large variety of grapes, of which 70 % are white varieties, 24 % are red varieties, and 6% are table varieties
- ✧ The total land area of vineyards is 147,000 ha (7%)
- ✧ Although Moldova ranks 13th globally in the harvested viticulture sector, it is 22nd in terms of grape production (0.8 % of total world grape production) and 2.1 % in European grape production
- ✧ This can be explained by the lower average yields per hectare (approximately 4.3 tha^{-1}) compared to the world yields (7.2 tha^{-1} in EU and 9.6 tha^{-1} at world level)
- ✧ The Moldovan wine sector has been one of the most significant agricultural subsectors in a predominantly agricultural economy

Mileștii Mici is the largest wine cellar in the world (it stretches for 200 km of the former limestone mine and holds almost 2 million bottles of wine)

Some suggestions for further research and adaptation to climate change policy:

- ✧ The risk of overwintering and summer crops being exposed to severe drought during their growing cycle is consequently increasing
- ✧ Cultivars should be developer to exploit the available moisture in wetter years combined with drought tolerance for years that lack optimum levels of precipitation
- ✧ An increasing tendency to grow the highest water consuming crops as well as a big increase in the area of row crops accelerated erosion, plagues of weeds, pests, and diseases
- ✧ The links between cropping patterns and water availability may also play a fundamental role in the reducing the cultivation of water demanding crops, and in improving irrigation efficiencies
- ✧ Local government could also adopt measures to relieve the decreasing water availability in RM and alleviate the negative effects of the increasing driver in demand

5.11 Products of condensation and desublimation

Condensation of water vapour results in the following products:

- dew, fog, and smoke from water droplets, clouds from water droplets

Desublimation of water vapour results the following products:

- hoar-frost (jíní), soft rime (jinovatka), frozen deposit (námraza), fog, smoke, and clouds of ice crystals
- they are formed by the contact of moist air with a body whose temperature is lower than the dew point temperature
- also referred to as horizontal precipitation

DEW

- it is formed in the above-mentioned manner at positive surface temperatures
- a common cause is radiation cooling of the surface at night
- ideally on cloudless nights with no wind
- in the Czech Republic, its amount does not exceed 0.3 mm during the night (max. 30 mm per year)
- in the tropics up to 2 mm per day
- it is an important source of water for animals and plants in times of water deficit
- phytopathological significance (development of fungal diseases)
- it usually not formed: on wood (wood does not cool and is porous), under trees (the tree is a barrier to radiated radiation - prevents the surface from cooling below), in the wind

HOAR-FROST

- it is formed by desublimation of water vapour in fog or smoke at negative temperatures (the surface is cooled by long-wave radiation)
- most often at a temperature lower than -8 °C
- has a coarser distinct crystalline structure in the form of needles or scales it falls when tapped (on cars; on things pulled out of the freezer)

- Frozen deposit
  - is formed in fog and wind at temperatures of 0 to -4°C by adhering and freezing droplets of supercooled water or by sticking ice crystals
  - at temperatures below -12°C, it is almost non-existent
  - it can be transparent, granular, or crystalline
  - it is developed in the form of slats against the direction of the wind
  - one-sided loading of objects → breakage (problem for trees, columns)

- Several types of icing:
  - granular - it is usually formed at temperatures between -2 and -10°C by rapidly freezing droplets of supercooled water, which is contained in fog or clouds, or is formed in contact with objects on the earth's surface or surfaces of aircraft
  - translucent icing - water droplets (fog or clouds) slowly freeze on objects, temperatures just below freezing 0 and -3°C, those water droplets before freezing fill the gaps between the surface structure - hold firmly on objects (breaking, dissolving)

GLAZE ice

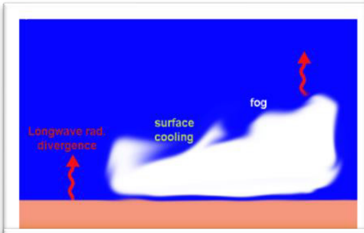
- does not form by condensation or desublimation on the surface
- it is caused by the impact of water droplets on a surface with a negative temperature
- are formed on horizontal and vertical or inclined surfaces, on branches and trunks of trees, on wires, on the earth's surface, on sidewalks, roads, etc.
- under the long-term conditions suitable for its formation, the ice layer can reach a thickness of several centimetres

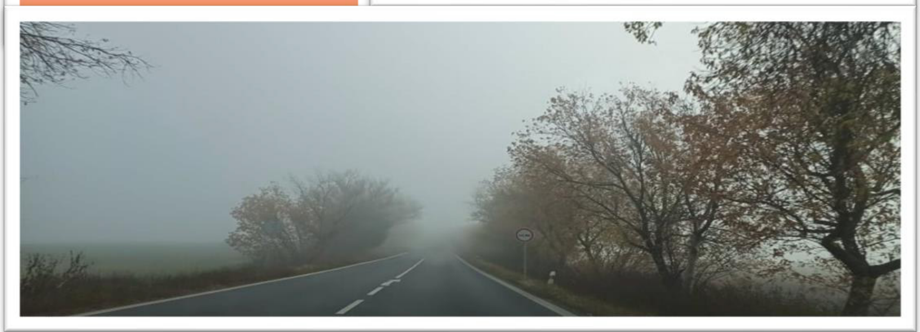
GROUND ice

- does not form by condensation or desublimation on the surface
- it is formed by melting snow and freezing the water again
- an ice layer covering the ground which is formed
- if uncooled raindrops or drizzle drops later on the ground
- if water from completely or partially melted snow on the ground freezes again
  - if icing snow occurs when operating vehicles on roads and paths

FOG

- suspension of water drops, or supercooled water drops or ice crystals in the air
- according to visibility:
  - weak (500-1000 m)
  - mild (200-500 m)
  - strong (50-200 m)
  - very strong (up to 50 m)
- in sight of 10 km, we are talking about smog

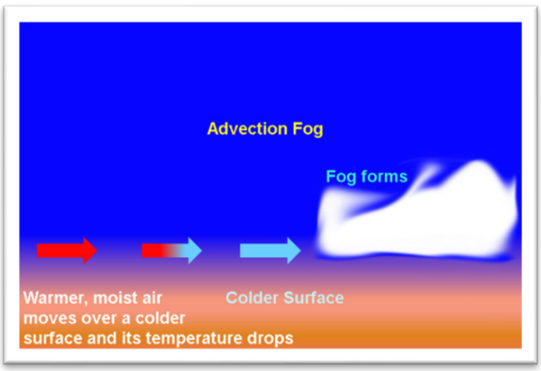




Division according to the cause of origin:

- radiation fog
- advection fog
- radiation advection
- mist from evaporation
- orographic fog
- frontal fog

Advection fog



- advection = horizontal flow
- relatively warm and humid air is pushed over the colder surface by advection – the air cools if the temperature is lower than the dew point temperature – condensation often accompanied by smog
- it also occurs above snow cover, even in the Arctic areas above the oceans of higher latitudes (in tropical oceans there is not much difference between air temperature and ocean temperature)

Radiation fog

- the surface is cooled by long-wave radiation, the adjacent layer of air is also cooled from it, if the temperature drops below the dew point temperature, the water condenses, and fog is formed
- this includes valley fog
- at night – decrease in air temperature, stopping the flow, 100% relative humidity
- the origin also depends on the type of surface on which it is formed (asphalt vs. vegetation – fog first forms over vegetation – asphalt cools longer, vegetation cools faster; there is often fog over the fields, not over the road)

Orographic fog

- it is created by adiabatic cooling of the air while overcoming obstacles
- it is difficult to distinguish such fog from low clouds
- a significant source of precipitation for plants (Canary Islands, Azores, Madeira – laurel forests – only northern windward sides at a certain altitude, occurrence of permanent fog – a significant source of moisture), a place where trade winds touch the surface

Frontal fog

- it is formed on atmospheric fronts by the mixture of two air masses with different temperatures

Ch5 Sources:

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  Video Microsoft Stream

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Chapter 6

New findings as a reflection of climate change – modelling the production potential of crops in the current and expected climate

Keywords

- crop growth changes
- yield parameters
- yield potential
- revenue from yield
- yield gap

Chapter 6: New findings as a reflection of climate change – modelling the production potential of crops in the current and expected climate

6.1 Linking crop production to climatic conditions

- ❖ crop production (CP) ⇒ depends on environmental conditions
- ❖ the link between CP and climatic conditions ranks this sector among the areas that may be most affected by climate change
- ❖ CP has a key role to play in addressing food security

- whether the yield will be more affected by the fertilization effect caused by the increased CO_2 concentration, or the impacts caused by the change of meteorological elements is estimated on the basis of the following two methods:

  1. based on field experiments carried out under controlled atmosphere conditions
  2. using growth models

6.2. Growth and development parameters of crops as an input to growth models (computer software)

- Crop growth and development (e.g., in spring barley) are called life cycle changes
    - ✓ they cover the period from the swelling and germination of the carcass to the creation of the new carcass
- Growth changes ☞ quantitative growth of organic matter, growth and differentiation of plant cells and tissues, formation of new plant organs and their spatial arrangement

- Qualitative changes ☞ transition of plants from vegetative to generative period, which culminates in the formation of reproductive organs (grains)
- to ensure growth, vegetation factors (nutrients, water, air) need to be available to the plants in at least a minimal amount
- for the course of developmental changes (differentiation of generative organs) plants need to meet limited requirements for external factors (developmental requirements), mainly temperature and light, to a certain extent acting in a specific time range (length of light day)

6.3 Methods for determining the crop yields

Production factors influencing crop yields (Fig 6.1)

⇒ Potential ☞ Determining factors – CO_2, radiation, temperature, crop characteristics: physiology, phenology, stand structure

⇒ Achievable ☞ Limiting factors – water, nutrients: nitrogen, phosphorus etc.

⇒ Current ☞ Reducing factors – diseases, pests, emissions, agrotechnics etc.

6.4 Growth models as part of large international projects

6.4.1 Global Yield Gap Atlas (GYGA) project – uses growth models

Objective: to increase food production to meet growing demand (www.yieldgap.org)

- agricultural land is evaluated here using the so-called "yield potential", "water-limited yield potential" and their difference with respect to the average real yield gap
- GYGA is looking for ways to reduce this gap and use water resources efficiently, which can be a major limiting factor in the agricultural sector
- the yield gap helps to estimate national and global food production, the production potential of existing agricultural land and water supply, or, according to different scenarios, to estimate whether additional agricultural land and water will be needed to meet expected demand
- the research priority is to inform agricultural policy about how to ensure global food security by interpreting trends in the yields of major food crops at regional and

national levels, identifying the regions with the largest yield gaps and proposing solutions to effectively reduce yield gaps

Actual yield data need to be disaggregated by water regime in those areas where irrigated and rainfed crop systems coexist. An estimate of actual yield needs to be determined:

For each crop x water regime x reference weather station (RWS) buffer combination

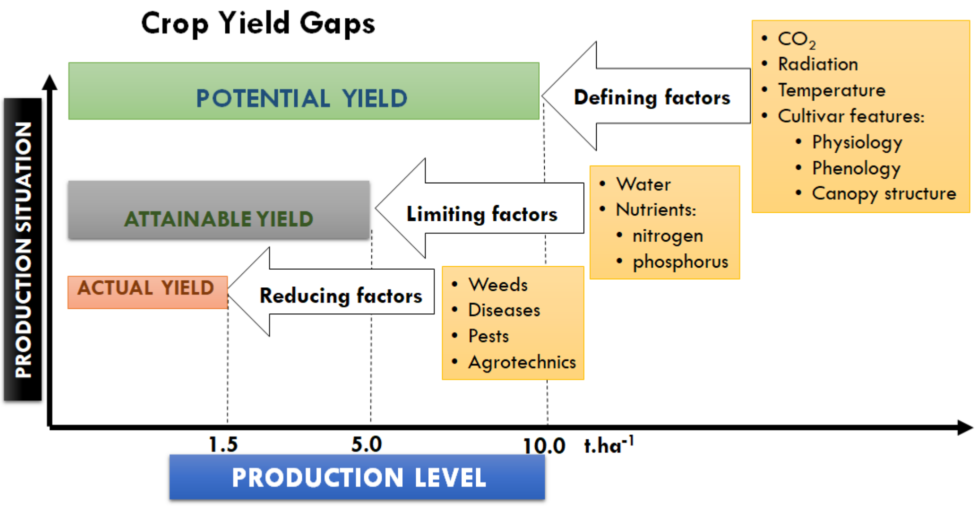


Fig. 6.1 The potential yield, attainable yield and actual farmers' yield of crops

6.4.2 FACCE-JPI initiative – uses growth models (www.faccejpi.com)

⇒ the aim is to contribute to Europe's bioeconomy while preserving and restoring ecosystem services in the context of current and future climate change

⇒ it addresses the impact of climate change on European agriculture and defines five main research topics:

a. the sustainability of food safety in the face of climate change based on modelling, benchmarking and a policy perspective
b. ecologically sustainable growth and intensification of agricultural systems in the current and future climate and availability of resources
c. assessing and reducing trade-offs between food production, biodiversity and ecosystem services
d. adaptation to climate change throughout the food chain, including market impacts,
e. reduction of greenhouse gas emissions caused by e.g., indirect land-use change, reduction of methane in agriculture and forestry etc.

Type of yield

Global Yield Gap Atlas

www.yieldgap.org

Yield potential (Y_p)

Y_p is the yield of a crop cultivar when grown with water and nutrients, non-limiting and biotic stress effectively controlled

Water-limited yield potential (Y_w)
Y_w is similar to Y_p, but crop growth is also limited by water supply, and hence influenced by soil type and field topography. Yw is used as a benchmark for estimating yield gaps only for rainfed crops, hence, Yw is not shown for irrigated crops.

Average actual yield (Y_a)
Y_a is defined as the average (of for instance the past 5 years for irrigated and 10 years for rainfed cropping systems) yield achieved by farmers in a given region under dominant management practices (sowing date, cultivar maturity, and plant density) and soil properties.

Yield gaps (Y_g) are estimated by the difference between yield potential (Y_p) without limitations due to water or other abiotic and biotic stresses (the most relevant benchmark for irrigated systems), or water-limited yield potential (Y_w) as the benchmark for rainfed systems, and actual crop yields (Y_a).

The crop yield gap is estimated as the difference between average simulated yield potential (Y_p, crop production without water stress) or water-limited yield potential (Y_w, rainfed crop production with water stress) and the average on-farm actual yield (Y_a).

That is, $Y_g = Y_p – Y_a$ or $Y_g = Y_w – Y_a$

6.4.3 MACSUR (Modelling European Agriculture with Climate Change for Food Security)

integrates the application of growth models from the areas of animal and plant production and business science (www.macsur.eu)

⇒ the aim is the technical and information integration of appropriate existing models and their application in regional case studies that reflect European diversity in soil, climate, social economy and agricultural systems

a. the main challenge is to find answers to the impact of variability and climate change on regional agricultural production systems and food production in Europe in general, in the near and distant future

b. the expected outcome of the project is to clarify the process for integrating models in assessing the impacts of climate change on agricultural production and assessing how the uncertainties of climate change impacts on European agriculture can be reduced through modelling

6.4.4 AgMIP Project (Agricultural Model Intercomparison and Improvement Project)

www.agmip.org

⇒ the aim is to improve global food security and strengthen the adaptive capacity of developing and developed countries to the expected impacts of a changing climate
   a. processing of historical data that has been realistically recorded
   b. modelling of probable future development using different climatic scenarios

6.5 Impacts of climate change on yields of major crops

6.5.1. Impacts of observed climate trends on yields of major crops

- climate trends have negatively affected yields in 79 % of wheat-growing regions, 70 % of maize-growing regions, 67 % of soybean-growing regions and 53 % of rice-growing regions
- annual crop production was affected by climate variability from 41 % (0.8 t/ha/year) for maize, 32 % (0.1 t/ha/year) for rice, 36 % (0.3 t/ha/year) for wheat and 43 % (0.5 t/ha/year) for soybeans
- in Europe, yields have risen by 24-39 %, but there has been a decline in yield growth /stagnation in recent decades, despite progress in breeding

6.5.2. Estimated changes in the level of yields caused by climate change during the 21st century

- impact projections vary by region, crop type and adaptation scenarios
- by 2050, the number of years with a drop in production caused by climate change will double *(every 5th year)*
- by 2100, one-third of the current yield will decline each decade
- 10% of future revenue projections for the period 2030-2049 assume an increase in revenue of more than 10%
- 10% of projections indicate revenue losses of more than 25% compared to the end of the 20th century

A summary of the expected changes in yields (wheat, maize, rice, and soybeans) caused by climate change during the 21st century for different emission scenarios in tropical and temperate areas (combined for examples "with" and "without" adaptation measures) indicates negative impacts more likely after 2050.

6.5.3 Median changes in yields according to the scenario with a continuous increase in CO_2

- the median yield changes for maize and wheat show a decrease in yields for low latitude areas (5-45%) and an increase in yields for higher latitudes (10-35%)
- in developing countries, agricultural productivity will fall by 10-15% of a unit area by 2080 (including the direct and indirect effects of higher CO_2 concentrations)
- in Europe, the potential for biomass production is expected to decline in thirteen of the fourteen sites tested, resulting in lower wheat yields
- the exceptions are, at the northernmost European wheat-growing areas, potential productivity will increase due to warming (however, soil quality may be a limitation)

a. Impacts of climate change

Climate change is just one of the factors that determines agricultural production

Climate changes

T & P changes, as well as extreme temperatures, flood events, pests and diseases, and ozone depletion are becoming increasingly important at higher levels of climate change.

CO_2

Crops respond to increasing levels of CO_2 in the atmosphere in various ways. In general, higher CO_2 concentrations act as a fertilizer on crops.

Technical development

Changes in food crop productivity in Europe between 1961 and 1990 were the strongest in terms of technological development; the effects of climate change were relatively small. This includes progress in the development of new seeds, improved plant protection, new and better sowing, cultivation and harvesting techniques and better fertilization.

Economy

Agricultural production is stimulated in regions that are relatively well situated, and trade flows of imports and exports are changing between these regions and regions with a sharp decline in crop yields.

b. Impacts of climate change

Climate change is just one of the factors that determines agricultural production

Climate changes | CO_2 | Technical development | Economy

Climate changes

Year-on-year variability in temperature and precipitation will increase in Europe in the future, especially in summer. Climate change has regularly led to the loss of yield in the past.

Crops are particularly prone to damage when stress from extreme weather events occurs during sensitive growth phases such as leaf formation, flowering or fruit development, and ripening. The consequences of spring drought may be more serious than the consequences of summer drought. In addition, damage caused by more frequent heavy rains and hail could increase. Especially when growing fruit, earlier flowering could be affected by a higher risk of frost.

Ground-level ozone, created by the photochemistry of precursor gases originating mainly from human activities, is also detrimental to crop yields. More serious ozone pollution leads to significant crop damage worldwide, which reduces overall crop production.

c. Impacts of climate change

Climate change is just one of the factors that determines agricultural production

Climate changes

CO_2

Technical development

Economy

The growing season of crops is changing.

The conditions for growing crops in the summer season describe two measures:

- The length of the thermal growing season is the length of the growing season of crops and trees. It starts when the daily average temperature in the spring rises above the selected threshold and ends when the average temperature in the fall falls below this level.
- The intensity of the thermal growing season is the sum of the effective temperatures: the cumulative sum of the daily average temperature exceedances above the threshold during this period. The commonly used base temperature for the thermal growing season is 5 °C in boreal and temperate climates and 10 °C in warmer climates.

d. Duration of the growing season in Europe

Past:
In Northern Europe, the period of heat growth extended by approximately 1 week between 1951 and 2000. The intensity of this extension increased throughout Europe after 2000.

Future:

- In most of Europe, the temperature of the growing season will last 1.5-2.0 °C months longer in 2100 compared to 1971-2000 for the peak climate change scenario and 20-40 days longer for the mild climate change scenario.
- The intensity of the thermal vegetation period relative to the 5 °C baseline (sum of daily growth rate) will be 60–100% higher in 2100 for the peak climate change scenario; the increase is somewhat smaller in the mild scenario. The increase in intensity this season is the largest in the south. In relative terms, however, the increase is largest in cold areas.

The growing season of crops is changing

Advantages:
Longer and more intensive growing seasons are especially advantageous for northern Europe. It allows the introduction of new species and cultivars in agriculture and allows greater use of the alternation of two crops. In addition, the mildness of the winter makes it easier for winter trees and other vulnerable perennials to over-winter.

Disadvantages:
Long growing seasons and mild winters favor pests and fungi, and higher temperatures in late autumn are of little use for plant photosynthesis in northern Europe due to limited light. Annual cereals are also harvested in early autumn, which is why they benefit from the autumn extension of the thermal growing season. At the end of the autumn, the harvest conditions would be unfavorable in any case due to the high humidity, even more so because precipitation is expected to increase, and the low amount of sunlight can no longer dry the harvest itself. In southern Europe, negative impacts dominate, mainly due to excessive heat and reduced water availability.

e. Impacts of climate change

Climate change is just one of the factors that determines agricultural production

Climate change

CO_2

Technical development

Economy

Another effect of rising temperatures is the loss of organic carbon from the soil due to the increased rate of decomposition and mineralization of organic material in agricultural soils. This loss of organic carbon reduces soil fertility and contributes to the greenhouse effect through carbon dioxide emissions. Studies have shown that rising temperatures by 2100 will lose 20-30% of Europe's soil carbon. A 40-60% reduction in soil organic carbon is possible if changes caused by climate change and expected land-use change are considered.

Climate change is just one of the factors that determines agricultural production

Climate changes

CO_2

Technical development

Economy

Crops respond to increasing levels of CO_2 in the atmosphere in various ways, and generally higher concentrations of CO_2 have a "fertilizing effect" on crops.

Along with increased biomass production, a corresponding increase in root organic matter is also expected, which can lead to permanent enrichment of the soil with organic matter.

- In the short term, increasing CO_2 concentrations may stimulate photosynthesis, leading to increased biomass production in C_3 crops such as wheat, barley, rye, potatoes, and rice.
- The response is much smaller for C_4 crops such as maize. These benefits will be particularly pronounced in northern Europe.
- For these crops, CO_2 fertilization fully compensates for the negative effects of heating by 1-2 °C for the effect of the global average yield.
- The effects of CO_2 fertilization should not be overemphasized, as available water supplies will be a factor on which yields depend in the first place. In addition, increasingly frequent weather extremes can pose risks to agricultural production.

The difference between corn on the one hand and wheat, rice and soybeans on the other is particularly relevant because these crops have different photosynthetic carbon cycles. Therefore, they react differently to changes in atmospheric CO_2 concentrations.

Climate change is just one of the factors that determines agricultural production

Climate changes

CO_2

Technical development

Economy

Past:
Between 1977 and 2005, winter wheat yield in France increased by an average of 1.69% per year due to technology, and similar trends were observed for winter and spring barley. This positive trend is stronger than the expected negative trend of declining yields on climate change. Global wheat production roughly doubled between 1970 and 2015, mainly due to better farming and higher crop yields.

Changes in food crop productivity in Europe between 1961 and 1990 were the strongest in terms of technological development; the effects of climate change were relatively small. This includes progress in the development of new seeds, improved plant protection, new and better sowing, cultivation and harvesting techniques and better fertilization.

Future:
For the period up to 2080, crop productivity in Europe is estimated to increase by 25-163%, of which 20-143% is due to technological developments and 5-20% is due to climate change and CO_2 fertilization.

It cannot be concluded that technological improvements will easily offset the effects of climate change. After all, the impact of technological improvements on crop yields has shown a decline in growth in recent decades. If this trend of slowing revenue growth due to technology is expected to continue in the future, the expected combined effects of climate change and technological change are positive: yields are expected to increase, especially in milder warming scenarios.

6.5.4. Vulnerabilities and Opportunities – Global Revenues

Corn, rice, soybeans, and wheat are four crops that form a major part of the scientific literature on climate impacts on crops. Together, these crops represent approximately 20% of the value of global agricultural production, 65% of the harvested area and almost 50% of the calories directlv consumed.

Temperature changes have reduced global yields of corn by 3.8% and wheat from 1980 to 2008 compared to the hypothesis without climate change of 5.5%. The effects on rice and soybean yields were small in the main production regions and worldwide.

Without climate change, the current average global yield of maize, wheat, and soybeans would be 4.1, 1.8 and 4.5% higher respectively. No significant effects were found on rice.

The uncertainties in these estimated impacts on revenues are large. For maize, the 90% probability interval is -8.5 to + 0.5% (- means yield loss, + increase). For wheat, these intervals are -7.5 to + 4.3% and -8.4 to -0.5%, respectively. These estimates include uncertainties related to the positive impact of higher CO_2 concentrations on crop yields.

Vulnerabilities and Opportunities – Global Revenues

<u>Geographical differences</u>

- ⇒ on a global scale, global warming appears to have so far increased crop yields in medium and high latitudes and decreased them at low latitudes
- ⇒ this pattern was observed in all crops. The effect of temperature change on yield appears to outweigh that of change in precipitation. However, changes in precipitation (more drought) are very important in the Mediterranean
- ⇒ in high latitudes, where low temperatures and snow cover are the primary limiting factors for crop production, warming has benefited crop growth
- ⇒ the mid-latitudes are in the transition zone between the changes that occurred in the low and high latitudes
- ⇒ at low latitudes, current temperatures are already high, and warming has led to more crops being exposed to physiologically critical temperatures

6.5.5 Vulnerabilities and benefits – pests and diseases

Observation:
• Pests are responsible for 10 to 16% losses in world crop production (like post-harvest losses).
• There is a significant trend of increasing observations of pests and pathogens in higher latitudes, globally and in the northern and southern hemispheres. Although recent climate change is included as an important driver of these observations, other factors such as new crop varieties and agricultural technologies could affect the results.
• Published observations of 612 crop pests and pathogens show that the average shift in the recorded incidence of these pests and pathogens since 1960 is 2.2 ± 0.8 km/year for the Northern Hemisphere and 1.7 km/year for the Southern Hemisphere.
Projection:
• Crop production losses due to pests are increasing globally with increasing temperatures.
• When average global surface temperatures increase by 2 °C, the average increase in crop losses due to pest pressure is 46, 19 and 31% for wheat, rice, and maize respectively.

→ The impact on wheat is relatively high: wheat is usually grown in a relatively cold climate, where warming will increase pest population growth and winter survival, leading to large population growth during the growing season.

→ The impact on rice is relatively low: rice is grown in a relatively warm tropical environment, where warming reduces the growth rate of insect populations, as current temperatures are almost optimal.

→ The impact on maize is between wheat and rice: this crop is grown in some regions where insect populations will increase and in other regions where populations will decline almost equally.

6.5.6 Vulnerabilities and Benefits – Global Revenue

More than 1700 published simulations for wheat, rice and corn

1920s: the majority of yield changes will be negative from the 1930s; 1940s, and 1950s: More than 70% of projections indicate declining revenues; After the 1950s: more than 45% of all projections for the second half of the century indicate a decline in revenues of more than 10%. Yield losses are greater in the second half of the century than in the first

- treatments are more effective for wheat and rice than for corn; the largest yield losses for wheat can be avoided, or even reversed, in tropical areas up to 2-3 °C local warming and in temperate areas over a wide range of warming

- over the centuries, increasing variability in yields seems increasingly likely
    - Warming reduces global yields of wheat by 6.0 ± 2.9%, rice by 3.2 ± 3.7%, corn by 7.4 ± 4.5% and soybeans by 3.1 ± 5% per °C of the global average temperature increase

Wheat

- non-irrigated wheat yields fell (<5%) worldwide at +1.5 °C in the major wheat belts of the North American Great Plains and Europe
- larger losses are seen in the northern Australian basin of Murray-Darling, eastern South Africa and northern Argentina, while western Asia and the North China Plain show significant yield increases
- irrigated crops react in the same way as non-irrigated crops

Maize

- non-irrigated maize yields are falling in most parts of the world at +1.5 °C

- when global warming ranges from +1.5 to +2.0 °C, yields of maize without irrigation continue to decline
- irrigated crops react in the same way as non-irrigated crops
- large yield losses of irrigated corn are found in most of North America, China and southern Europe
- the global maize yield is expected to decrease by 10-20 % with each temperature increase of 1 °C without adaptation
- the use of adaptation strategies encouraged by farmers by changing the planting date and crop variety can mitigate the effects of 0.5 °C warming on maize yields; However, temperatures above 1 °C will negatively affect yield in most countries

Soya

- in a +1.5 °C world, soybean yields are expected to improve in much of eastern Europe and northwest Asia and decline slightly in inland North America and the equatorial parts of South America and East Asia

- for soybeans, adaptation (including planting earlier in the season and variety changes) may be effective at temperatures up to 4 °C

<u>Rice</u>

- changes in world rice yields with a temperature of +1.5 °C are small in the main production regions in Asia, while yields are expected to increase in tropical Africa and South America

- without the effects of CO_2, the production of all four crops in the world with +2 °C would be lower compared to the current situation
- however, thanks to the effects of CO_2, the yields of wheat, rice and soybeans in the world are improving at +2 °C in almost all regions of the world, the effect of CO_2 fertilization largely overcomes the negative effects of temperature and precipitation

Climate change is just one of the factors that determines agricultural production

Climate change

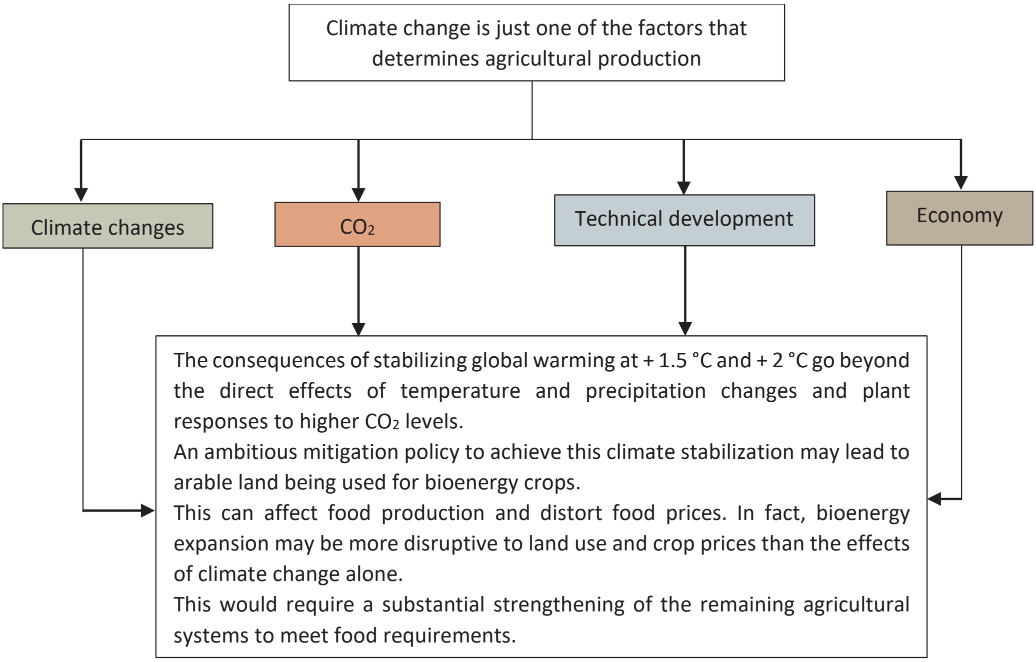
CO_2

Technical development

Economy

The combined effects of higher temperatures, higher atmospheric CO_2 levels and trade effects focused on seven crop types: temperate maize, soybeans, wheat, sugar cane, cotton, tropical corn, and tropical soybeans. Regional agricultural impacts at 1.5 °C warming cannot be distinguished from impacts at 2 °C warming. Uncertainties about the contributing effects of climate, CO_2, and trade, and how they interact or reinforce each other, are simply too great. The results are dominated by uncertainty about the effect of CO_2 fertilization on crop yield. Without the impact of CO_2 fertilization, the agricultural sector is generally worse in the 2 °C scenario than in the 1.5 °C scenario.

Taking all the uncertainties into account, it cannot be concluded whether 1.5 °C is better or worse than 2 °C warming in terms of the global impact on agriculture.



6.5.7 Climate change impacts and adaptations in cropping practices in the Republic of Moldova

In the Republic of Moldova, almost twice as many farmers will not be considered economically viable if drought conditions continue to worsen in areas that are currently under severe drought (75%). Drought affects decisions by farmers. Farmers grow some crops, which the authors consider untenable in the long term with a view to profit.
Adjustments to sowing time (15%), the introduction of more drought resistant cultivars (11%), the use of crop protection measures (9%), and shifting to new crops (8%) seem to be minor and moderate adaptation practices employed by farmers. The improvement of drainage and irrigation systems, the conservation of water, and the diversification of crop production are measures adopted by only a tiny proportion of farmers to respond to crop failure.

- The sharp decline in the productivity of winter wheat was attributed to lower yields under a higher frequency of droughts and heat stress, and the short duration of the grain-filling period, though changes in management may also have played a role
- The use of cultivars with black frosts and rain deficit as well as cultivars with later sowing dates and earlier harvesting dates are assumed to be important adaptationmeasures for winter wheat
- The cropping system is not keeping pace with climate change, as is the case for maize systems in RM, where the warming and drought that occur between growing and final seed usage result in unintentionally shorter crop duration (earlier sowing dates and earlier harvesting dates)

- ✧ Drought and heat stress often occur simultaneusly during the flowering stage of sunflower which led farmers to use new drought resistent cultivars with high temperature requirements
- ✧ The introduction of new extra-early varieties and crop protection are expected to be more important in the case of potato
- ✧ The higher occurrence of weed or disease was picked up by most respondents. Potato productivity drops due to the spread of insects during droughts

Ch6 Sources:

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  Video Microsoft Stream

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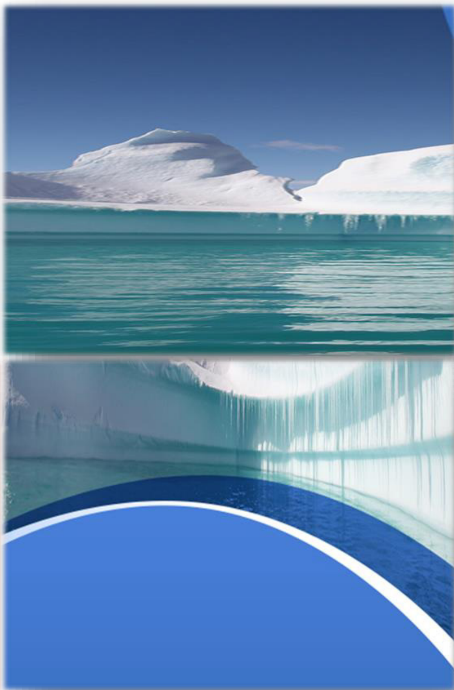
Chapter 7

Classification of models, description, and sources of uncertainties associated with their outputs



Keywords:

- numerical model of the atmosphere
- climate model
- global Climate Models **(GCM)**
- regional Climate Models **(RCM)**
- **AGCM**: Atmospheric Global Climate Model
- **AOGCM**: Atmospheric – Ocean Global Climate Model
- **GCM**: Global Climate Model or Global Circulation

Chapter 7: Classification of models, description, and sources of uncertainties associated with their outputs

7.1 Recommended programs for climate system simulations

The Community Climate System Model (CCSM) is a coupled climate model for simulating the earth's climate system. Composed of four separate models simultaneously simulating the earth's atmosphere, ocean, land surface and sea-ice, and one central coupler component, the CCSM allows researchers to conduct fundamental research into the earth's past, present and future climate states.

7.2 Classification of models

A. Numerical model of the atmosphere

- its description of basic dynamic and physical properties of various components of the atmosphere and their interactions in a suitable computer form with the necessary approximations

B. Climate model

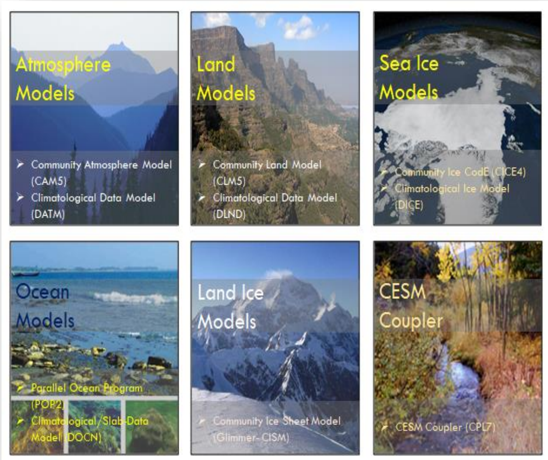
- one-dimensional models (radiation or surface processes)
- two-dimensional models (surface processes, dynamics)
- three-dimensional models (radiation, surface processes, dynamics)

C. Hydrological models

- models used in operational hydrology
- models applied for design and project activities in the field of water management
- models used in research

D. Dynamic growth models

- close cooperation with the European scientific community



- meteorologists, modelers, hydrologists, climatologists, physicists, engineers, national meteorological and hydrological service, WMO, EUMETSAT and ESA

7.3 Numerical model of the atmosphere

Weather forecast model

A. Parameterization

- the physical process is described by some simplified computational scheme with the help of simple parameters contained in the equations
- dynamic equations in the model:
  - Newton's second law of motion
    - ✓ the horizontal acceleration of a certain volume of air is influenced by the horizontal pressure gradient, friction, and the deflection force of the Earth's rotation
- hydrostatic equation
  - the pressure at a certain point is given by the mass of the atmosphere above it, vertical accelerations are not considered
- continuity equation
  - ensures the preservation of matter

Fig. 7.1 Supercomputer server for numerical modelling of the atmosphere

B. Model physics:

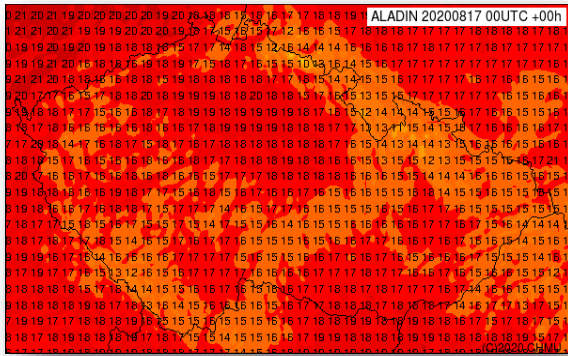
- equation of state of gases
- thermodynamic equation (law of conservation of energy)
- parameterization of humidity processes (e.g., evaporation, condensation, cloud formation and distribution)
- parameterization of radiation processes (absorption and emission of various types of radiation)
- parameterization of convective processes
- parameterization of the exchange of the fluxes of momentum, heat and water vapour at the interface of the atmosphere and water surfaces
- the equations in the model are differential, e.g., they describe the processes in which quantities (e.g., pressure, temperature) change with time and place
- if the magnitude of the change of a certain quantity is known, its magnitude can be calculated in the next time step – the repetition of this procedure is integration
- integration of equations – the new values of all necessary quantities are calculated for subsequent time steps – this expresses the predictive ability of the model

Model ALADIN (Limit Air, Dynamic Adaptation, International Development)

In recent years, the model has also been intensively developing methods for refining initial conditions, both by assimilation of observations (three-dimensional variational assimilation of data) and a sophisticated combination of global analysis and simulation of inter-scale structures (blending methods).

ALADIN:

- a numerical limited weather forecasting model designed for short-term forecasting of atmospheric processes on a meso-beta scale (10 km)
- based on a system of basic equations solved by the spectral method on bounded domains by a semi-implicit semi-lagrangian scheme
- the integration area of the model is plotted on the map in a conformal projection, a hybrid coordinate system is used in the vertical
- the model is updated at 00, 06, 12, and 18 UTC (universal time coordinated)



- the calculation of the weather forecast for three days in hourly steps takes about 4 hours
    - the German COSMO model is updated every three hours, which increases its overall accuracy
    - in the US, regional models are then updated every hour
    - a new generation of models for meso-gamma prediction is being developed within the ALADIN-2 project (with a spatial step of 2 km)

7.4 Climate Models

Modelling climate development: past, present, and future

Climate model → simulates the state, behaviour, and possible development of the Earth's climate system

Main components of the climate model

- radiation (radiation absorption, radiation)
- dynamics (horizontal energy transfer, vertical movements – convection)
- surface processes (albedo, radiation, surface atmosphere interactions)
- temporal and spatial resolution

Climate simulation options

a. Simulation of the regional climate on Earth depending on the overall climate, and also on its possible changes → climate scenarios
b. A true prediction of climate change on Earth

Success of climate change modelling on Earth

We do not know all processes such as:

- feedback on the absorption of energy coming from the Earth's Sun and the emission of this energy into space ⇒ the chemistry of the atmosphere, the amount of greenhouse gases (water vapor, carbon dioxide, methane, and ozone)
- regularities that control solar activity, related to radiation in different parts of the spectrum and which is reflected in the cycles of sunspots
- influence of changes in the motion of the Earth around the Sun ⇒ ellipticity of the Earth's orbit around the Sun
- the influence of the precession of the direction of the Earth's axis on the amount of energy coming to us from the Sun ⇒ geographical distribution of incident solar radiation on the Earth's surface
- future volcanic activity that affects temperature through the emission of volcanic dust into the atmosphere

Summary:

- At present, we do not yet know all the necessary physical properties of the Earth's climate system, its atmosphere and cosmos, especially the activity of the Sun, to accurately model

Classification of climate models

1. One-dimensional models
   (a) Energy Balance Models (EBMs)
   (b) Radiative-Convective Models (RCMs)
2. Two-dimensional climate models (SDMs – Statistical Dynamical Models)
3. Three-dimensional climate models (GCMs – General Circulation Models)

1. One-dimensional models

(a) Energy Balance Models (EBMs)

- they indicate the balance between energy intake and expenditure in the vertical column of the atmosphere, limited by the upper limit of the atmosphere and the active surface
- distribution of the surface into zonal strips of width 10º → application of the equation to vertical columns above these strips (Q_s is calculated using the solar constant, the other members of the equation are parameterized according to the ground temperature)

$A = Q_S (1 - \alpha_S) - I_S$

A – gain or loss of heat due to atmospheric or ocean circulation
Q_S – solar radiation incident on the upper limit of the atmosphere
α_S – albedo of the Earth-atmosphere system
I_S – long-wave radiation emitted into interplanetary space

(b) Radiation-convective models (RCMs)

- the atmosphere at *RCMs* is divided into several layers and for each of them the equilibrium temperature is calculated from the balance of shortwave and longwave flows under the assumption of radiation equilibrium

2. Two-dimensional climate models (SDMs – Statistical Dynamical Models)

- significantly more complicated than one-dimensional models
- represent either two horizontal or one vertical and one horizontal dimension (combination of width dimension EBM and vertical RCM) (Fig. 7.2)
- more realistic parameterization of width energy transport
- rather limited for future climate projections (poor zonal resolution – replaced by GCMs)

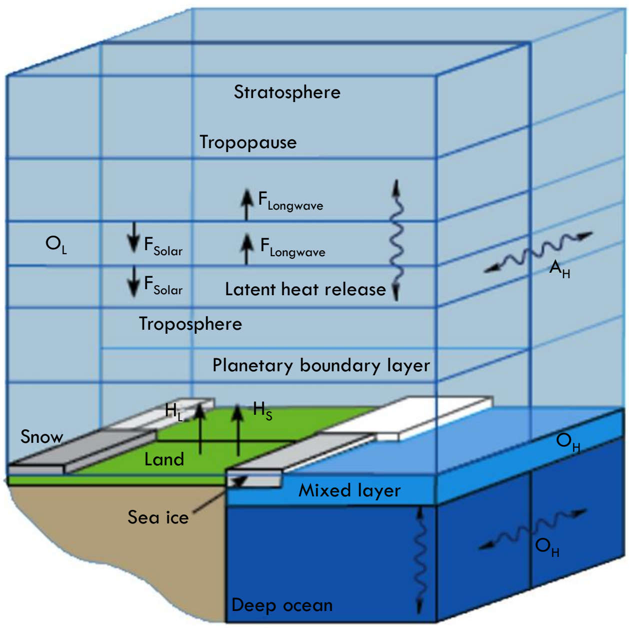


Fig. 7.2 Two-dimensional climate models (SDMs – Statistical Dynamical Models)

Source: modified after de Haan et al., 1994.

3. Three-dimensional climate models (GCMs – global circulation, global climate)

Calculation procedure:

- calculation for so-called grid points with different network steps and for several layers (levels) in the atmosphere

- some physical processes are not described by the above equations – the scale of these phenomena is smaller than the network step (e.g., convective processes, precipitation) → only their final effect (parameterization) is inserted into the models
- problem connecting GCM with ocean circulation

- Coupled models of atmospheric and ocean circulation (AOGCMs)

a) swamp models – the ocean as a solid earth surface with an unlimited supply of water for evaporation

b) input of ocean surface temperature from climatic observations

c) models with a mixing layer – heat capacity and processes in the layer 30–70 m are considered

d) ocean circulation models (OGCMs) – response of deep ocean waters (problem of different time scale of processes)

Basic equations for three-dimensional climate models:

- calculation for so-called grid points with different network steps and for several layers (levels) in the atmosphere (Fig. 7.3)
- the first thermodynamic theorem (energy conservation): energy input = increase of internal energy + work done
- Newton's second law of motion (conservation of momentum): force = mass · acceleration
- continuity equation (conservation of mass during fluid flow): the sum of the gradients of the product of density and wind speed in three orthogonal directions is zero
- equation of state of gases (ideal gas law): pressure – volume = gas constant – absolute temperature

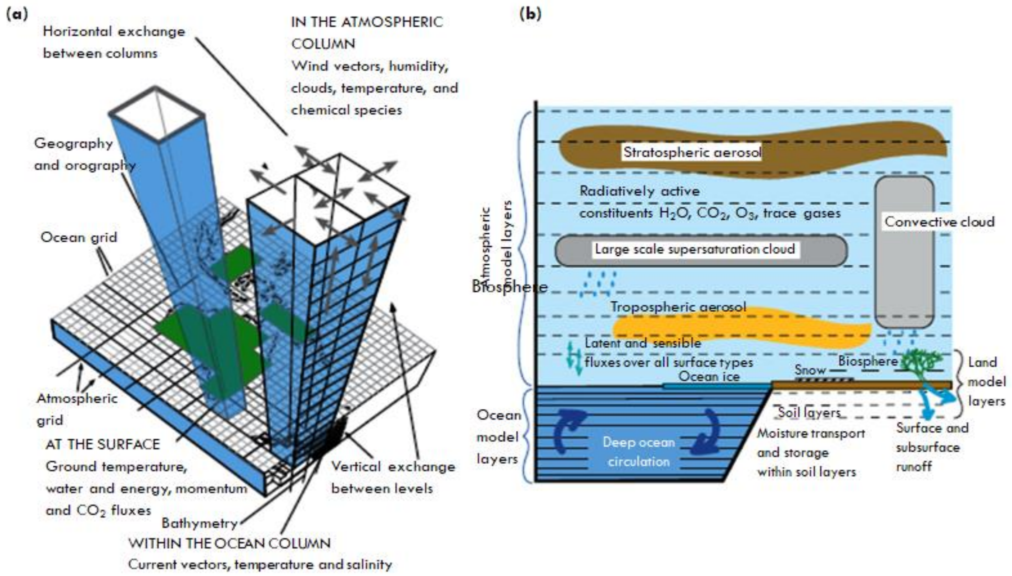


Fig. 7.3 Discretization (splitting into layers and boxes) is a basic characteristic of all three-dimensional climate models. The resolutions of the atmosphere, ocean and surface models frequently differ. (a) The atmosphere as a set of interacting columns of 'boxes' distributed around the Earth on a grid. (b) Processes in a single column of a 3D coupled climate model including various types of cloud, soil layers and tropospheric and stratospheric aerosols

Source: modified after Hansen et al., 1983

The Atmosphere Model (AGCM) itself consists of three parts:

- dynamic part – contains equations of motion, mass transport of dry air and water vapor, energy conversion on a large scale
- physical part – includes radiation schemes, formation and distribution of clouds, atmospheric precipitation, release of latent heat
- additional part – describes the transfer of mass, momentum, latent and apparent heat between the atmosphere and the earth's surface and also includes surface topography and vegetation

Estimation of future climate development using models

⇒ GCM – a tool for simulating the state, behaviour and development of CS

- they are based on the solution of equations of motion and thermodynamics, equations of state, equations of radiation energy transfer, equations of heat balance of the earth's surface and equations of water balance of the earth's surface
- calculation for grid points with different network steps and for several levels in the atmosphere
- in the atmospheric part of the model, the resolution is 2–4 °; in the ocean 0.5–1 °

- 25-40 levels in the atmosphere and 20-30 levels in the ocean
- relatively small spatial resolution (hundreds of km)

  ⇒RCM – belongs to the techniques of so-called downscaling
  - the simulation does not take place for the entire planet Earth, but only for limited areas (domains)
- it modifies the reaction of the planetary scale to capture the physical effects of topography.
- they are based on numerical weather prediction (NWP), which explicitly simulate the development of processes in the atmosphere and contain parameterizations of important dynamic and physical processes
- they use boundary conditions from the controlling GCM
- horizontal resolution approx. 10 km

Time evolution of climate models (gradual addition of other CS components to the model; Fig. 7.4)

1890s: Radiation-convective transmission
1960s: Hydrological cycle
1970s: Sea Ice – Continent Surface
1990s: Chemical processes in the atmosphere
2000s: Aerosols – Vegetation
2010s: Biogeochemical cycles – Carbon cycle

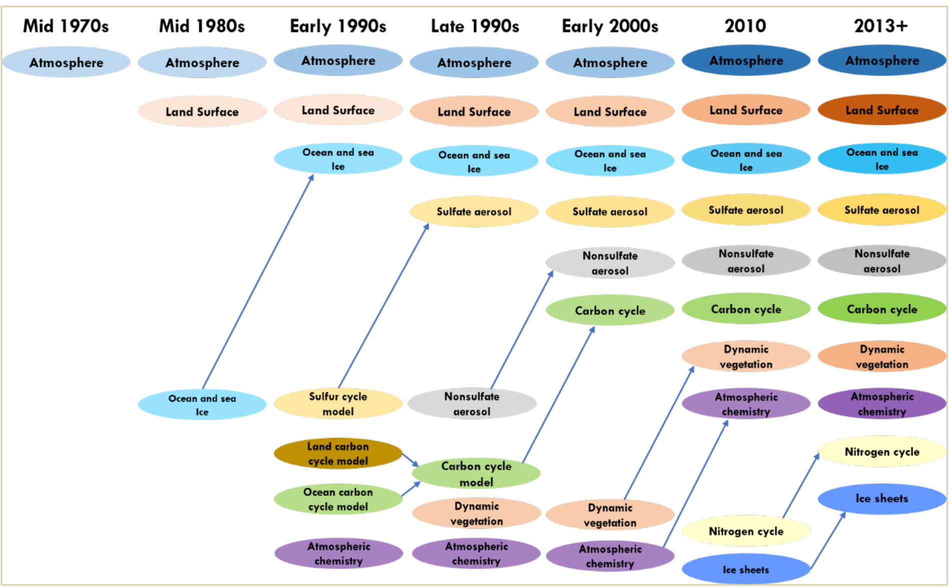


Fig. 7.4 Changing list of components (ingredients) of climate models as it evolved over the past half-century. Global climate model arcs 1960-2013

Source: extended and modified from IPCC, 2001

The first important feedback is the connection associated with the circulation in the oceans:
The feedback associated with water vapour and its geographical distribution depends on the detailed processes of evaporation, condensation and advection, as well as on convection. These processes are affected by higher surface temperatures. All these phenomena are already sufficiently included in the weather forecasting models; water vapour feedback has been studied very carefully. The most important of the other feedbacks is cloud-related feedback and ocean current feedback. Weather forecast models and most climate models so far use relatively simple schemes to incorporate the effects of clouds. For example, a typical model allows you to consider three types of clouds (low, medium, high), each of which has prescribed values of reflectance and transmittance to radiation. For a cloud that is the result of large-scale atmospheric movements, the presence or absence of the cloud in the model is determined by the so-called humidity threshold. If the relative humidity is above the threshold (usually around 90%), the cloud is considered to exist; if the humidity is below this value, no cloud will form in the model. The threshold humidity value can be determined experimentally to ensure that the average cloud cover is modelled in approximately the same way as in the real atmosphere. To describe the formation and development of convective clouds, it is necessary to include a special parameterization in the model, the so-called convective scheme. Incomplete knowledge of the mentioned link represents the greatest uncertainty in the model predictions.

The second important feedback is the connection associated with the circulation in the oceans:
Compared to the global atmospheric model, the most difficult problem in formulating a climate model is the inclusion of the influence of the oceans. The first models, which included only the surface layer of the ocean, had very limited capabilities.
To more accurately describe the influence of the oceans, it is necessary to model the circulation in the oceans and connect this model with the model of atmospheric circulation. In order to be able to carry out the calculations with the current computer technology, the distances between the nodal points in the horizontal direction cannot be less than about 300 km. Usually, heat, water, and friction exchange between the ocean and the atmosphere. e.g., fresh water falls from clouds in the form of precipitation, has an effect on ocean flow – it affects the distribution of salt, which affects the density of ocean water. Therefore, the climate described by the model is very sensitive to the size and location of water heat exchange at the ocean-atmosphere interface.

7.5 Energy Balance Models

A. *Coupled global climate model atmosphere – ocean*

- in the last 50 years, the nature of experimental strategies for climate models has evolved significantly as our knowledge and skills have increased

B. *Atmosphere – Ocean – Biosphere – Lithosphere – Cryosphere connection in models*

- modern models connecting the ocean and the atmosphere are constructed as modular components connected by a coupling member (centre), a program that transfers flows between the components of the model
- a simple example of a climate model calculation based on solar radiation and average temperature. The resulting output is the albedo of the surface

Application of GCM to model the response to the growth of CO_2 concentrations

Finding out the response of CS to the growth of greenhouse gas concentrations:

- control climate: based on the initial and boundary conditions corresponding to the current climate e.g., the current concentration of CO_2 or equivalent CO_2, (e.g., the concentration of CO_2 corresponding to the radiative forcing of all greenhouse gases together), the calculation is performed for several model years to decades, the circulation gets into a quasi-stationary state ➡ from the values of the variables corresponding to this equilibrium state, the "control climate" is calculated, also $1{\cdot}CO_2$ (it should correspond to reality as best as possible)
- experimental climate: the calculation is repeated for the changed input values of CO_2 (e.g., $2{\cdot}CO_2$) until the equilibrium of the model circulation is reached ➡ from the corresponding values of the variables the "experimental climate" is calculated, also $2{\cdot}CO_2$
- the difference of both simulated climate states ($2{\cdot}CO_2$ minus $1{\cdot}CO_2$) represents a model response of the climate system to a radiation failure caused by the growth of CO_2 in the atmosphere
- equilibrium studies – a step change in the concentration of greenhouse gases is expected (does not correspond to reality)
- transient studies – a continuous increase in greenhouse gases is expected, where the model climate gradually passes through a series of equilibrium states (smaller realized temperature change compared to the expected equilibrium change)

Climate Scenario

- a probable expression of the future climate, designed for explicit use in studying the potential impacts of anthropogenic climate change
- it must include anthropogenic climate change and its natural variability
- is usually a combination of a climate change scenario with a description of the current climate (expressed by observation)
- it is not a prediction of the future climate, but rather a description of alternatives to the probable future, considering the conditions under which they may occur
- clarifying uncertainties in identifying possible climate change limitations with regard to different development paths

Climate Scenario Requirements

- vary according to geographical area, type of impacts and purpose of impact studies
- key variables: maximum and minimum temperatures, precipitation, solar radiation, relative humidity, wind speed (hereinafter: CO_2 concentration, sea ice, pressure, sea level, frequency of stormy tides)
- must affect the degree of uncertainty – future greenhouse gas emissions, their conversion to atmospheric concentrations, the response of different models to radiation exposure, model differentiation
- consistency between the different components of the scenarios
- multiple scenarios to reflect multiple sources of uncertainty
- scenarios for impact studies – combining climate change estimation with baseline climatology
- spatial and temporal resolution

Criteria for suitability of scenarios after impact studies (Fig. 7.5 – 7.6):

(a) Consistency at the regional level with global projections

- regional climate change scenarios may be outside the bounds of global change, but must be consistent with theory and model results

(b) Physical plausibility and reality

- climate change must be physically plausible, so that changes in various climate variables are mutually consistent and plausible

(c) Suitability of information for impact assessments

- scenarios must present climate change on an appropriate temporal and spatial scale for a sufficient number of variables and include an appropriate time horizon applicable to impact estimate

(d) Availability

- information for the development of climate scenarios must be readily available for use in impact studies

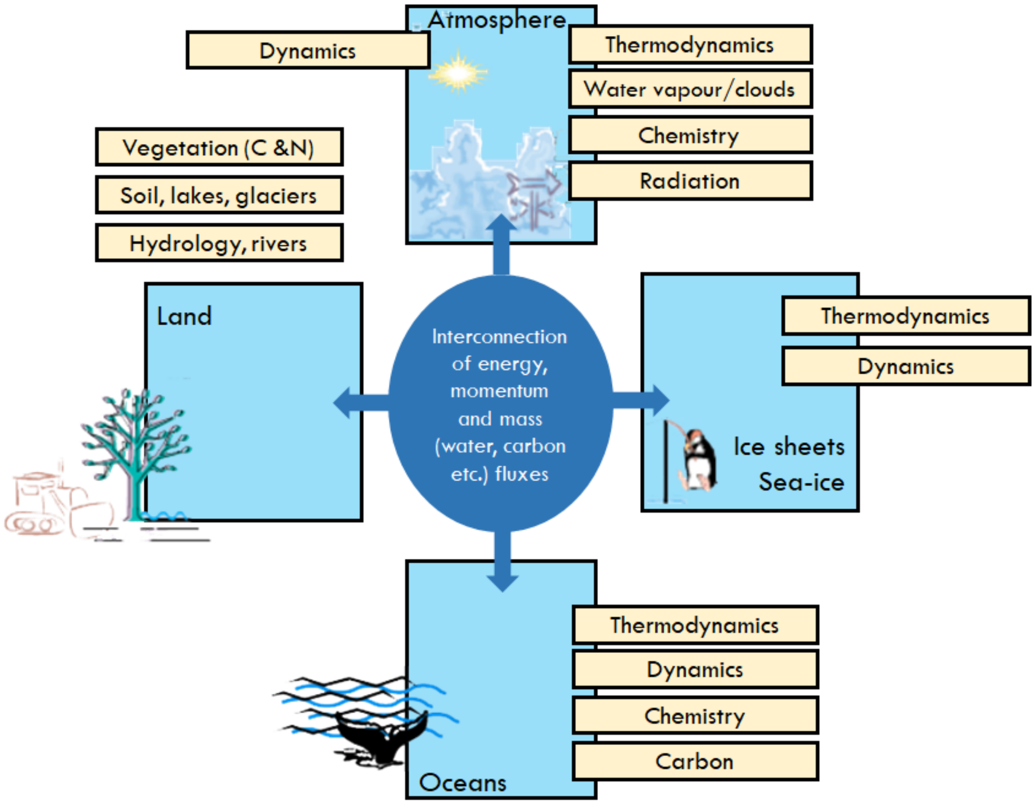


Fig. 7.5 Modern coupled ocean–atmosphere models are constructed as modular components connected by a coupler (centre), a program that transfers fluxes between the model components

Source: modified after Moss et al., 2010.

- this is the reference period from which estimated future climate changes are calculated (1961–1990 and others; ideal would be a period in the 19th century when the anthropogenic effect on climate was negligible)
- model estimates of future climate change are applied to the climate of the base period (differences, ratios)
- defines the current climate, with which the climate change scenario is usually combined

Sources of uncertainties associated with the outputs of climate models

- ➢ current science cannot accurately describe all the processes in the climate system
- ➢ the mechanisms of atmospheric-ocean energy transfer or carbon cycle feedback have still not been sufficiently elucidated

Sources of GCM and RCM uncertainties

- initial conditions, boundary conditions, parameterization, and model structure
- the uncertainty associated with the initial conditions is due to the chaotic nature of the climate system

- the dependence of model simulations on the accuracy of the given initial conditions is considered to be more pronounced for NWP models than CM
- boundary conditions of the simulation:
  (a) GCM – amount of incident solar radiation and amount of greenhouse gas emissions
  (b) RCM – boundary condition is the course of quantities simulated by GCM
- uncertainties in model simulations can be analyzed
  (1) according to the ability to simulate the control climate and compare it with station data (% agreement)
  (2) according to the deviation of projections of the CM from a set (so-called ensemble) of selected models (max. 40 models)

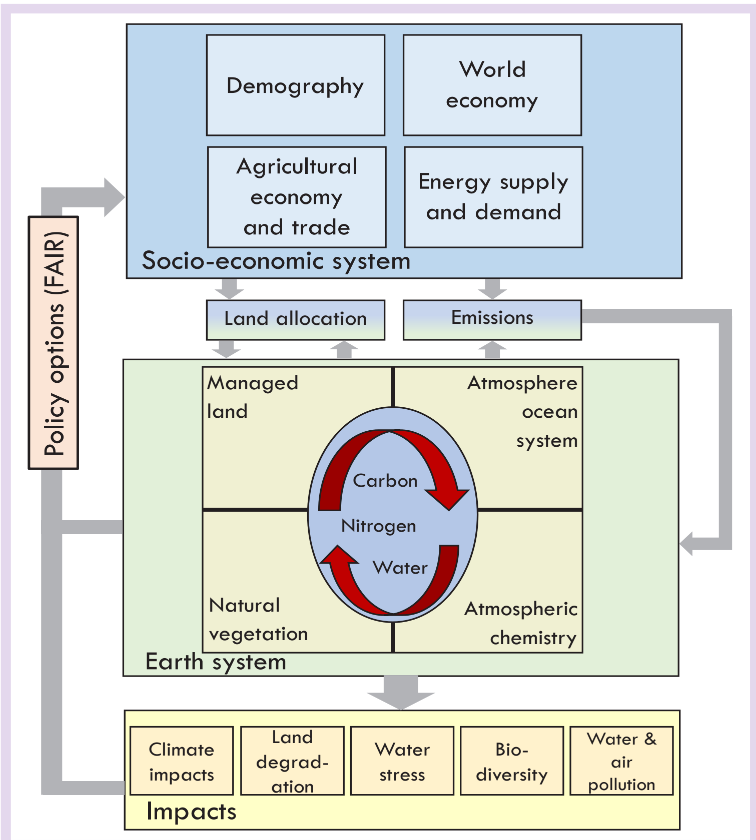


Fig. 7.6 Integrated assessment models in climate system. Impacts, adaptation and vulnerability of human settlement and infrastructure, ecosystems, energy and economy

Source: modified after Bouwman et al., 2006.

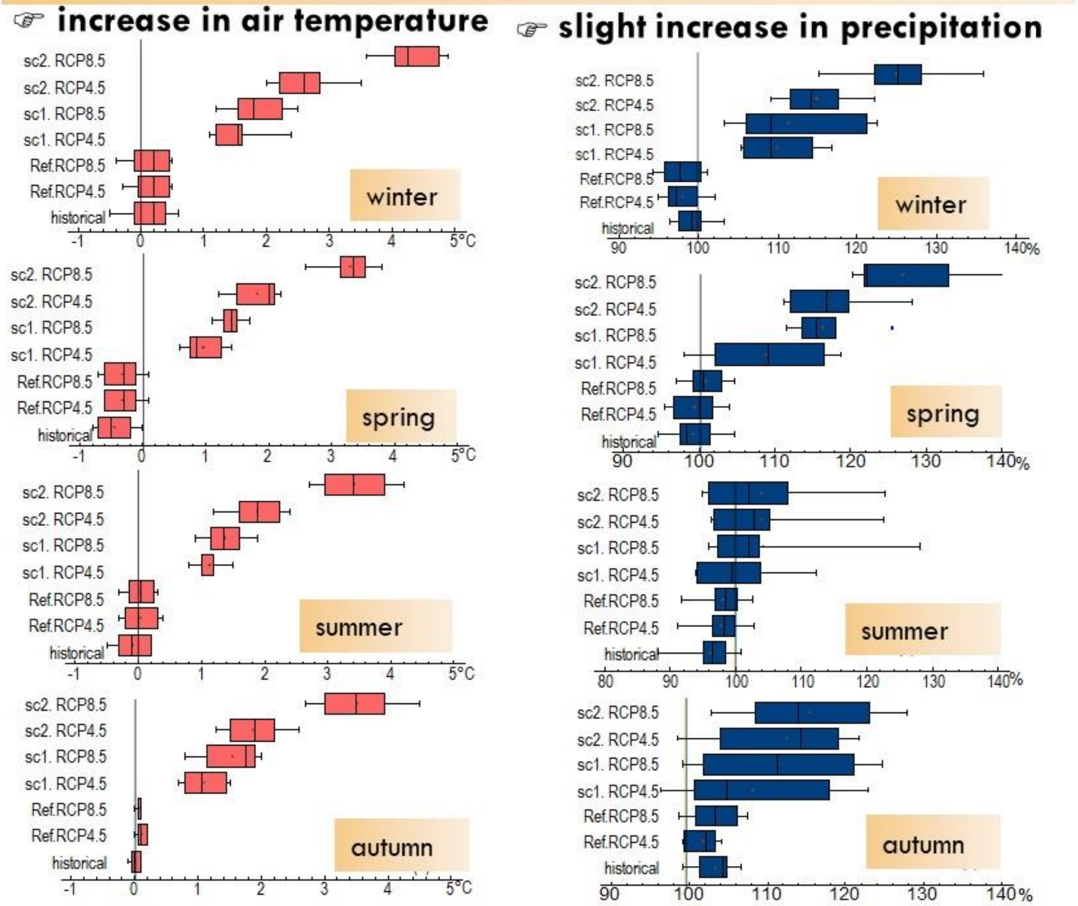
The simplified simulation in the climate model is divided into several phases:

- the first phase ➡ verify that the atmosphere equalizes with the ocean and these values (heat currents, etc.) are used as input values to the next phases of the model
- the second phase ➡ is set so that the values of greenhouse gases in the atmosphere are set to pre-industrial values
- the third phase ➡ CO_2 values are twice the pre-industrial values. The question is whether at this concentration of CO_2 the modelled climate will stabilize at a certain value after some time or whether it will be unstable (in other words, whether the oceans will not start cooking on your computer or the globe will freeze)

7.7 Projected changes in temperature and precipitation

- Box plots summarizing ranges of the seasonal mean temperature and precipitation projected for the historical and future periods from eight RCMs forced by the RCP4.5 and RCP8.5 scenarios.
- Based on all the experiments, the annual air temperature will increase by 1.6–2.6 °C (RCP4.5) to 3.1–4.1 °C (RCP8.5) by the end of the 21st century compared to the reference period.
- Most of the temperature changes showed highly robust and statistically significant warming, with seasonal differences.
- The highest increase in the winter temperatures was approximately 4.9 °C at the end of the 21st century.
- The projections for the annual total precipitation increase from 7 (mid-century) to 13 % (the end of the century) under the RCP4.5 scenario, and from 6 to 16% under RCP8.5.
- The largest change can be seen in the winter, with an increase of up to 35 % towards the end of the century, while the smallest change is seen in the summer months.

Modeled change of air temperature and precipitation in the CR according to Euro-CORDEX models



Modeled change of average air temperature and total precipitation according to the scenario RCP4.5 and RCP8.5 for individual seasons and time horizons (sc1. 2041-2070 and sc2. 2071-2100 with reference period 1981-2010 (Ref)) in the Czech Republic.

Ch7 Sources:

- Potopová, V. (2021). Study materials published on Moodle – teaching system for teaching support at the Czech University of Life Sciences in Prague. Available from https://moodle.czu.cz/. Lecture 7: Classification of models, description, and sources of uncertainties associated with their outputs

Video Microsoft Stream

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Chapter 8

Linking climate, economic and growth models as tools for predicting the development of the food production process in relation to climate change

Keywords:

- compound events (CEs)
- crop growth simulation
- Soil – Plant – Atmosphere
- economic models
- GLOBIOM

Chapter 8: Linking climate, economic and growth models as tools for predicting the development of the food production process in relation to climate change

8.1 Understanding of the compound events (CEs)

Concurrent droughts and heatwaves may significantly influence agriculture, although the individual events involved may not themselves represent severe extremes. The role of multivariate extremes, compound events and storyline tools in agricultural research has thus gained more attention. Compound events may lead to amplified impacts on agricultural production compared to individual events and have received increased attention in recent years.

The dual concept of crop losses and CEs has been suggested as an approach to understand extreme impacts and reduce farmers' exposure to weather-related financial risks. However, a weakness of the CEs approach is the challenge of developing parametric models that reliably capture the yield losses experienced by farmers.

Regional key risks under climate change in Europe (IPCC, AR6, 2021):

Climate change contains the high frequency and intensity of compound climatic events which can increase water scarcity. The negative impacts of climate change have put obstacles to improving the agricultural productivity in south-eastern Europe which has affected people to severe food and water insecurity.

- Heat stress and mortality to people due to increasing temperatures and heat extremes.
- Terrestrial ecosystems disruptions with increasing precipitation variabilities and drought.
- Water scarcity and risk of freshwater resources with consequences for ecosystems.

Hop production can be an example for demonstrating the wide-ranging effects of compound events when the impacts depend on multiple dependent climate variables. Hop (*Humulus lupulus* L.) is a globally important crop and is grown especially for its secondary metabolites (e.g., hop oils, α- and β-acids), which are used in beer brewing to add bitterness and aroma to beer (Fig. 8.1).

Fig. 8.1 Hop use for the special green beer in Czechia

Hop yards are exposed to an ensemble of CEs whose impacts are complex and difficult to assess. Figure 8.2 summarizes the impact of compound wet-cool and dry-hot thresholds on hop production, although each of these individual conditions may not necessarily be extreme. Both extreme dry-hot and cool-wet thresholds lead to lower alpha–acid contents and can also decrease the yield of hop cones. Exposure to strong wind, for example, can cause leaf damage and some loss of cone-bearing laterals, both of which affect bine health and yield. From flowering to maturity, exposure to hot winds can also negatively affect cone quality.

Simultaneous heatwaves and drought events (i.e., a period of consecutive extremely hot days and low precipitation) lead to the expansion of weeds, many of which are C4 plants, and have a higher water use efficiency compared to C3 plants. These CEs in turn contribute to increases in insect populations; hop cultivars that have been weakened by drought are generally less resistant to insects and other pests.

Furthermore, storms, hail, and longer rain periods with high air humidity led to damaged plant tissues, stressed plants, and easier infection by fungal diseases (e.g., *Pseudoperonospora humuli*).

The occurrence and distribution of hop Peronospora are very closely related to concurrent variations in air temperatures, relative air humidity and precipitation amounts. These pests and diseases cost overseas producers millions of euros annually in crop loss and crop protection expenses. In previous years, the susceptibility of the hop crop to a range of pests and diseases has significantly affected market prices.

Rising demand and lower yields have driven the increases in hop prices over the past decade. Climate change affects three of beer's core ingredients, namely, hops, water, and barley. Therefore, the impacts of CEs on hop production and the adverse impacts of climate change have been recognized as one of the greatest challenges of the 21st century. Decreases in the global supply of barley lead to proportionally larger decreases in barley used to make beer and ultimately result in dramatic regional decreases in beer consumption and increases in beer prices.

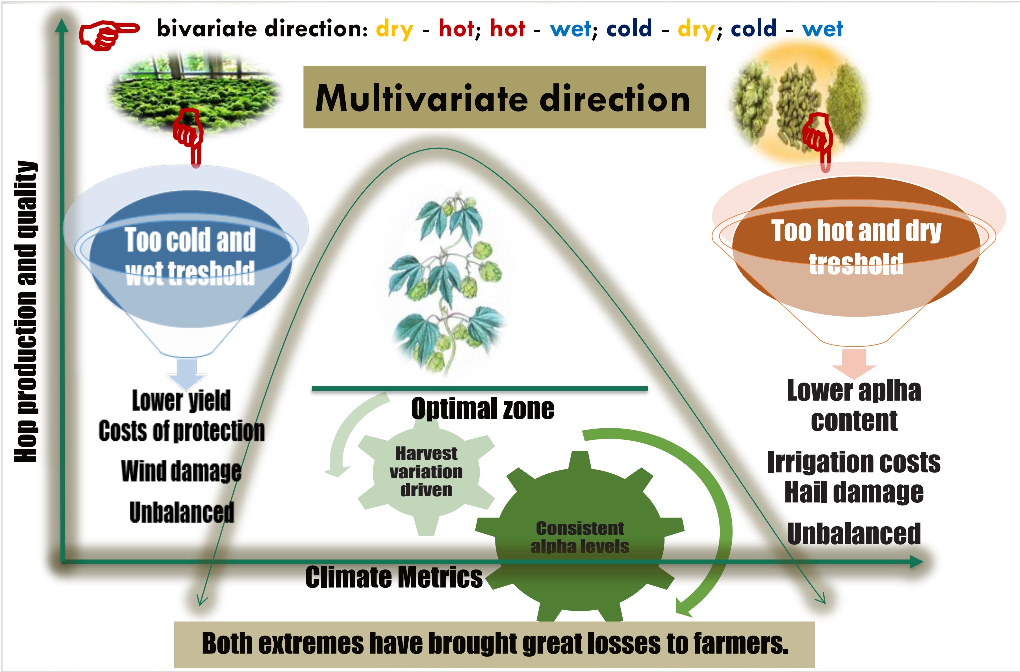

Fig. 8.2 Scheme of integration of multivariate directions of hop production, quality, and CEs

What is a compound event?

(i) a combination of processes that leads to a significant impact
(ii) when two or more individual extreme events occur jointly in some regions
(iii) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined

8.2 Modelling the impacts of compound climate and weather events on Agro-food system

The impact of a loss in productivity on prices requires both crop, livestock, and economic modelling. Scientists try to develop several scenarios that can illustrate how the food system will respond to compound events of climate extremes.

- The dual concept of crop losses and compound CEs has been suggested as an approach to understand extreme impacts and reduce farmers' exposure to weather-related financial risks

- The sustainable fodder production for livestock is exposed to an ensemble of CEs whose impacts are complex and difficult to assess
- CEs can contribute to increased water stress on fodder production, which will not keep the optimum demand for the livestock sector

Compound events and crop production: including lagged and indirect effects
e.g., dry-cool, dry-hot, wet-cool, wet-hot, irrigation-induced cooling, urban heat island-drought, yield losses-drought/heat-pests/diseases-market prices

Hazards such as floods, wildfires, heatwaves, and droughts usually result from a combination of interacting physical processes that occur across multiple spatial and temporal scales.

Examples of high-impact Compound Events include

(i) droughts, heatwaves, wildfire and/or air pollution and their interactions involving a complex interplay between temperature, humidity, and precipitation

(ii) extreme precipitation, river discharge and storm surge interactions, combining coastal storm processes with fluvial/pluvial and ocean dynamics

(iii) storms including clustering of major events leading to spatial and/or temporal dependence

Climate change alters many of these processes and their interaction, making projections of future hazards based on single driver analyses difficult. Impact studies considering only one driver usually fail to assess the extent of the impacts of CEs. A better understanding of the nature of CEs will strengthen the connection between climate science and risk management with immediate benefits to society. One of the platforms dealing with dynamic modelling and multivariate statistics, all inherently relevant for studying CEs, is the European COST Action DAMOCLES.

Compound climate events in which only one variable is extreme (e.g., either hot but no drought or extreme drought but not hot) and events in which both variables are extreme (e.g., drought and heat waves) may have different impacts on hop yields and alpha-bitter acid contents. Increasing occurrences of compound drought and heat events have led to increased income variability for beer production, and affected the major hop growers across Europe (EU).

Modelling the interactions between several compound events is more complex than modelling the drivers of individual events. Examples of how compounding climatic drivers and societal drivers interact to produce connected climate extremes (Tables 8.1–8.2). The societal drivers listed are non-exhaustive; additionally, only those that contribute directly to the hazard are considered, rather than those that contribute to the impact.

Table 8.1 Examples of compound events according to the proposed typology (modified after Zscheischler *et al.*, 2020)

Event	Modulators	Associated weather systems	Precondition	Climatic drivers	Hazard(s)	Potential impacts
Preconditioned						
Heavy precipitation on saturated soil	-	Tropical and extratropical cyclones, severe storms, warm conveyor belts	Saturated soil	Heavy precipitation	Flood, landslide	Infrastructure
Rain on snow	-	Extratropical cyclones	Snow-covered land surface	Heavy precipitation, snowmelt	Flood	Infrastructure
False spring	-	Cold front	Early budbreak due to warm temperatures at end of winter	-	Frost	Crops, natural vegetation
Multivariate						
Compound flooding	-	Tropical and extratropical cyclones	-	Precipitation, coastal water levels, river flow, wind speed, wind fetch, duration of high wind speeds	Flood	Infrastructure, human health
Compound drought and heat	Sea-surface temperature patterns	Atmospheric blocks	-	Temperature, precipitation, evapotranspiration, atmospheric humidity	Drought, heatwave	Wildfire, crops, natural vegetation, power plants, fisheries
Humid heatwave	-	Marine-air advection, tropical moisture export	-	Temperature, atmospheric humidity	Heat stress	Human health, energy demand
Compound precipitation and wind extremes	-	Tropical and extratropical cyclones, severe storms	-	-	Heavy precipitation, extreme wind	Infrastructure
Spatially compounding						
Spatially concurrent precipitation extremes/floods at regional scale	Large-scale climate modes	Storms, atmospheric blocks	-	Precipitation	Heavy precipitation, flood	Regional trade, (re-)insurance, shipping, emergency response
Spatially co-occurring climate extremes at global scale	Large-scale climate modes, circumpolar wave patterns	Dependent on the type of extremes	-	Temperature, precipitation, evapotranspiration, atmospheric humidity	Heavy precipitation, flood, drought, heatwave, frost	Global food system, globally operating (re-) insurance

8.3 Modelling the impact of compound events on crop production by the dynamic growth models

8.3.1 Crop modelling and climate change assessment

Continued pressure on agricultural land, food insecurity and required adaptation to climate change have made integrated assessment and modelling of future agro-ecosystems development increasingly important. Various modelling tools are used to support decision making and planning in agriculture. An important component in this is *crop modelling*.

Crop models and decision support systems can be useful tools for researchers, teachers, scientists, extension personnel, policymakers and planners to help and support the application and evaluation of sustainable and long-term alternative management practices. Crop simulation modelling can be a powerful tool to analyse the impact of the changing climate/weather impacts and to the introduction of new crops into existing cropping systems, providing that this approach is combined with field experiments. Cropping system models offer the potential for integrating the physiological understanding of crop characteristics and for examining how potential growth and major limitations to production might vary in different environments and with different management scenarios.

What is a crop model?

The crop models calculate expected growth and development based on equations that describe how a crop, as a community of plants, responds to soil and weather conditions. Computer simulation models of the soil-plant-atmosphere system can make a valuable contribution to both improving crop performance and predicting environmental impacts in different management scenarios.

Dynamic crop simulation models can be a useful tool to simulate the wide-ranging effects of CEs on crop production where impacts depend on multiple dependent weather-soil variables and crop management. For example, CEs have a huge impact on yield, speed of ripening and the presence of vitamins in the grown tomatoes (e.g., the lycopene concentrations).

8.3.2 Classification of crop growth models for prediction of crop production

The last two decades have witnessed the development of numerous crop-growth and yield simulation models describing the dynamics of the soil-plant-atmosphere system. Models are now available for all the major crops such as wheat, rice, maize, cotton, sorghum, groundnut, soybean, chickpea, potato, millet, and sunflower as well as for some plantation and horticultural crops (field-grown tomato). There are at least 100 different crop simulation models of varying complexity that presently exist. Here we are giving information about only six dynamic Crop Growth Simulation Models:

☞ DSSAT (Decision Support System for Agrotechnology Transfer; Hoogenboom *et al.,* 2010)
☞ HERMES (Highly Extensible Resource for Modelling Event-Driven Supply Chains; Kersebaum, 2007)
☞ EPIC (Environmental Policy Integrated Climate; Williams *et al.,* 1984)
☞ APEX (Agricultural Policy Environmental Extender; Williams, 2002)
☞ AquaCrop (FAO, 2009)
☞ APSIM (Agricultural Production System Simulator; Holzworth *et al.,* 2014)

DSSAT model

- it is a software application program that comprises crop simulation models for over 42 crops as well as tools to facilitate effective use of the models
- the tools include database management programs for soil, weather, crop management and experimental data, utilities, and application programs
- the crop simulation models simulate growth, development, and yield as a function of the soil-plant-atmosphere dynamics
- the crop models require daily weather data, soil surface and profile information, and detailed crop management as input
- crop genetic information is defined in a crop species file that is provided by DSSAT and cultivar or variety information that should be provided by the user
- simulations are initiated either at planting or before planting through the simulation of a bare fallow period
- these simulations are conducted at a daily step or in some cases, at an hourly time step depending on the process and the crop model
- at the end of each day, the plant and soil water, nitrogen, phosphorus, and carbon balances are updated, as well as the crop's vegetative and reproductive development stage

EPIC model

- it is a cropping systems model used to predict impacts of management of soil, water, nutrient, and pesticide movements with their combined effects on soil loss, water quality, and crop

- it was developed to simulate soil erosion effect on soil productivity and then was extended to simulate agricultural management effects on crop production, soil, and water resources
- it was extended to the whole farm and small watershed level to evaluate different land management strategies like sustainability, erosion, water supply and quality, weather, economics
- to evaluate the irrigation management for various crops to explore irrigation schedules for optimal yield and was applied for simulating crop yield, regional crop water requirements, water productivity and soil water dynamics for better crop irrigation management in the semiarid regions.

APEX model

- it is a modelling tool that includes directing water, sediment, nutrients, and pesticides across compound landscapes and channel systems to the watershed outlet
- it can be subdivided into relatively homogeneous soil, land use, management, and weather conditions
- it is capable of simulating irrigation, drainage, fertilization and manure management, crop rotation, tillage, pesticide management and it can also evaluate climate change impacts, global CO_2 and biomass production

HERMES model

- it is an agro-ecosystem model that can simulate soil-crop interactions with emphasis on water and nitrogen associated processes
- the model has the strength and capability to regenerate inter-annual unpredictability in yields, biomass, and soil processes under numerous field crop rotations
- the model has the potentiality to simulate mitigation and adaptation measures within the agricultural sector and can be used to predict the shifting in crop production and soil processes under climate change conditions and the potential to analyse the mitigation and adaptation measures

APSIM model

- the model is a crop growth model which was developed to simulate biophysical processes in agricultural systems
- the model can provide a prediction of different crop productions in relation to climate, soil, and crop management factors
- the model has the potential of exploring the productivity and water use efficiency (WUE) under irrigation management module for dryland farming systems

- it can be a useful tool to investigate the crop water management option in case of pre-crop (e.g., crop sequence, weed control, residue management) and in-crop (sowing time, planting density, nutrient management) management system, effective for seasonal climate forecasts and estimating yield gaps of numerous crops across climatic zones

AquaCrop

- AquaCrop is a crop water productivity model developed by FAO to improve water productivity in rainfed and irrigated fields
- it simulates yield response to water of herbaceous crops and is particularly suited to address conditions where water is a key limiting factor in crop production
- AquaCrop was developed in 2009 and since then it has been used worldwide in different agro-ecological conditions

8.4 Modelling the impact of compound events on livestock farming

The direct and indirect effects of global warming, combined with the increasing frequency of weather extremes, are also serious issues for livestock production, even in temperate climates such as Central Europe (Fig. 8.4). The dual concept of crop losses and CEs has been suggested as an approach to understand extreme impacts and reduce farmers' exposure to weather-related financial risks. Sustainable fodder production for livestock is exposed to an ensemble of CEs whose impacts are complex and difficult to assess. CEs can contribute to increased water stress on fodder production, which will not keep the optimum demand for the livestock sector.

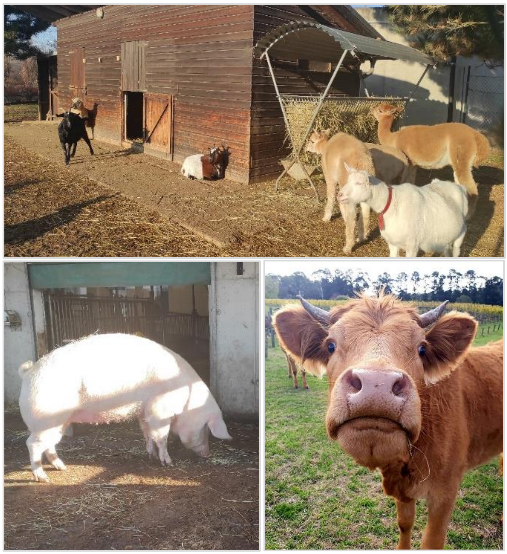

Fig. 8.4 Experimental livestock farm for students inside the CZU campus

Future climate change and adaptation measures for livestock

Adaptation measures for livestock will need to be established:

- mainly due to its burden caused by rising spring and summer temperatures, as well as an increasing number of consecutive tropical days
- an increase in temperature can lead to a reduction in net livestock yield, while increased total precipitation has a positive effect on livestock production

- if the increase in temperature is greater, then the effect of high temperature on the animals is strongly negative
- these conditions are causing thermal stress in animals.
    - they cause a lower milk yield and weight gain in cows
    - high-yielding cows are particularly sensitive to heat stress
- stress conditions will occur in both stables and pastures, and animal yields are likely to be reduced
- In addition to rising temperatures, regional and local impacts on livestock farming are also amplified by changing the humidity regime and airflow
- because livestock is responsible for 12% of anthropogenic greenhouse gas emissions, measures to reduce these emissions are likely to be needed, as emissions from livestock can be expected to increase by 16 Gg of ammonia and 0.1 Gg of methane per year under anticipated heat stress conditions

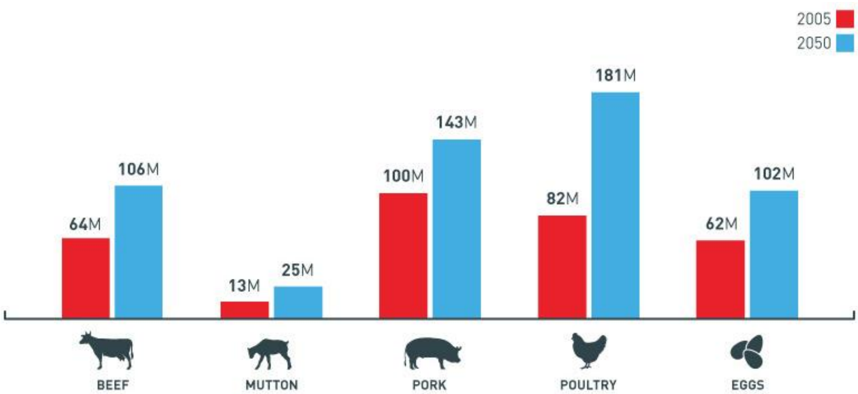

Fig. 8.5 Global demand for meat (2005 vs 2050) *Source: FAO, 2012*

8.5 Integration of livestock and crop production

- feed supply, herd size reduction, livestock diversification and forage cropping, as well as changes in production systems, animal husbandry strategy and management. The global demand of livestock and poultry production needs to increase to feed the growing population (Fig. 8.5)
- fodder crop vegetation has soil–water interaction effects on surface hydrologic processes (e.g., increases infiltration capacity and erosion control), soil organic matter accumulation, soil aggregation, prevention of soil crushing and soil aeration
- an estimated 5.5 Gt of carbon is stored in European grassland (30% of total European agricultural land) within the top 30 cm soil profile
- an average of 25% livestock protein intake comes from grassland in Europe where alfalfa together with maize are key field crops for semiarid environments.

"The climate impact of a certain sector is evaluated through its annual greenhouse gas emissions, typically using the Global Warming Potential over a 100-year period metric– GWP100– which estimates the change in atmospheric energy balance resulting from a particular type of GHG emission. However, as GHG emissions are reported as CO_2-equivalents (which is a very stable GHG), GWP100 can fail to capture how the relative impacts of different gases change over time. Given the short atmospheric lifetime of methane, which not only delivers climate effects on a relatively short time horizon, but also contributes to climate change, this makes it an interesting and essential element in agricultural mitigation policy design.

The methane specificities – by which we mean a significant warming effect and related mitigation potential in the short term and the "climate neutrality" of a stable level of emissions in the long term – deserve distinct treatment in climate mitigation policies. EU commitment engaged to reduce particularly global methane emissions by at least 30% from 2020 levels by 2030".

Source: https://iiasa.ac.at/news/dec-2021/how-we-measure-effects-of-methane-matters-for-climate-policy

How effective is the promotion of low-meat diets at reducing greenhouse gas emissions compared to carbon pricing when the effectiveness of mitigation policies is measured against methane's long-term behaviour?

An international team of researchers (IIASA) explored how focusing either on the short- or long-term warming effects of methane can affect climate mitigation policies and dietary transitions in agriculture.

The livestock sector and its production system parameterization are based on the animal-level model.

RUMINANT model

- It is an animal-level model that simulates the effects of nutrition (feed quality and availability) on the growth and production of beef, lamb, and poultry meat, bovine and small ruminant milk and eggs.
- Model consists of a dynamic section that estimates intake and the supply of nutrients to the animal from the knowledge of the fermentation kinetics and passage of feed constituents (carbohydrate and protein) through their gastrointestinal tract and their subsequent excretion.

Summarization:

- ✓ **Stringent climate policies might lead to reductions in food availability of up to 200 kcal per capita per day globally.**
- ✓ **Mitigation policies targeting emissions from land-use change are 5 to 10 times more efficient – measured in "total abatement calorie cost" – than policies targeting emissions from livestock only.**
- ✓ **Fostering transitions towards more productive livestock production systems in combination with climate policies targeting the land-use change appears to be the most efficient lever to deliver desirable climate and food availability outcomes.**

8.4 Economic models

Future farm support programs in Europe will probably reduce direct payments and increase the resources for agro-environmental programs. At the same time, global change (e.g., climate change, population growth, changing nutrition regimes) requires a major increase in the productivity of agriculture. These developments will enforce the search for new technologies, specific fostering of ecologically desired activities and the development of new organizational forms.

Farm-level modelling is a strong tool to improve the organization of farms, test the economic viability of new technologies and ensure acceptance of new agro-environmental programs.
To improve the quality of this type of models, a review of existing tools and an investigation of the requirements of stakeholders are needed.

Key questions: How does climate change impact international trade, both within Europe and with third world countries?

8.6 Global Biosphere Management Model (GLOBIOM)

Three basic segments of modelling global change:
Atmosphere – climate development and its modelling
Ecosystems – carbon cycle, impacts of global change on managed ecosystems, including the design of mitigation and adaptation measures
Socio-economic systems – impacts on the development and behaviour of society

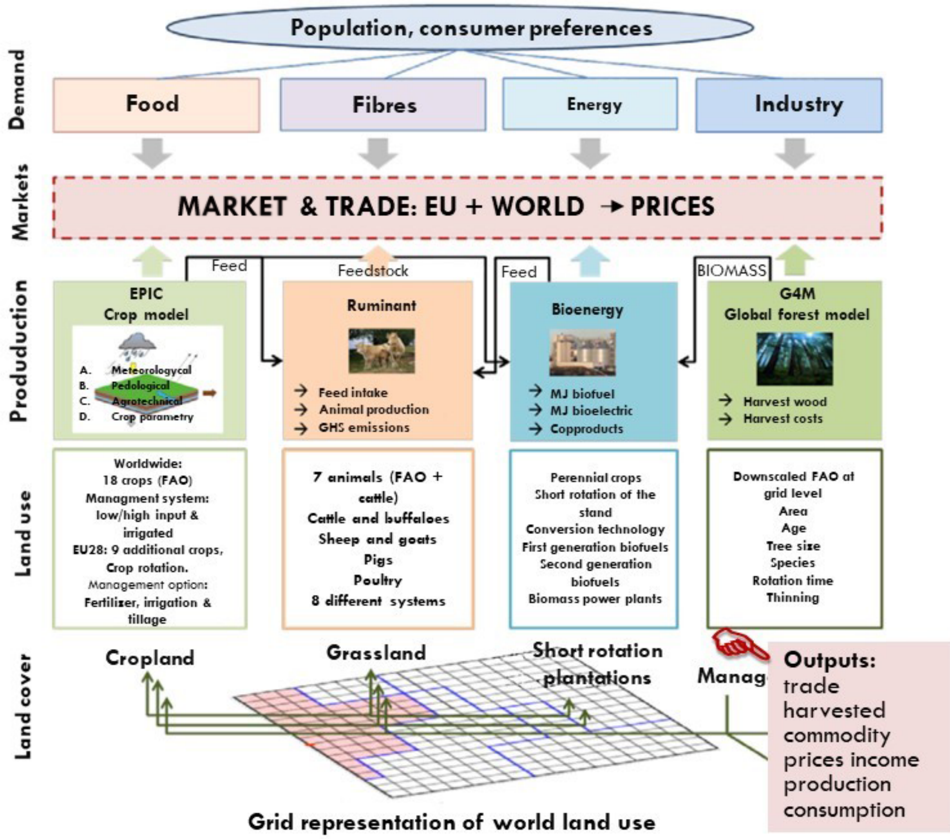

Fig. 8.6 Linking climate, economic and growth models as tools for predicting the development of the food production process in relation to climate change

Source: modified after Hasegawa *et al.,* 2018

Vulnerability assessment of livestock, estimation of the meteorological aspects of climate change, using a business-as-usual production model Global Biosphere Management Model (GLOBIOM) and adaptation strategies based on estimates of irrigation demands are needed to attain sustainable fodder production. A comprehensive economic model Global Biosphere Management Model (GLOBIOM) provides a detailed description of production possibilities at a high spatial resolution, considering the availability of grazing areas and fodder as well as various crop feed mixes across systems and regions. GLOBIOM is developed by the International Institute for Applied Systems Analysis (IIASA, Fig. 8.6).

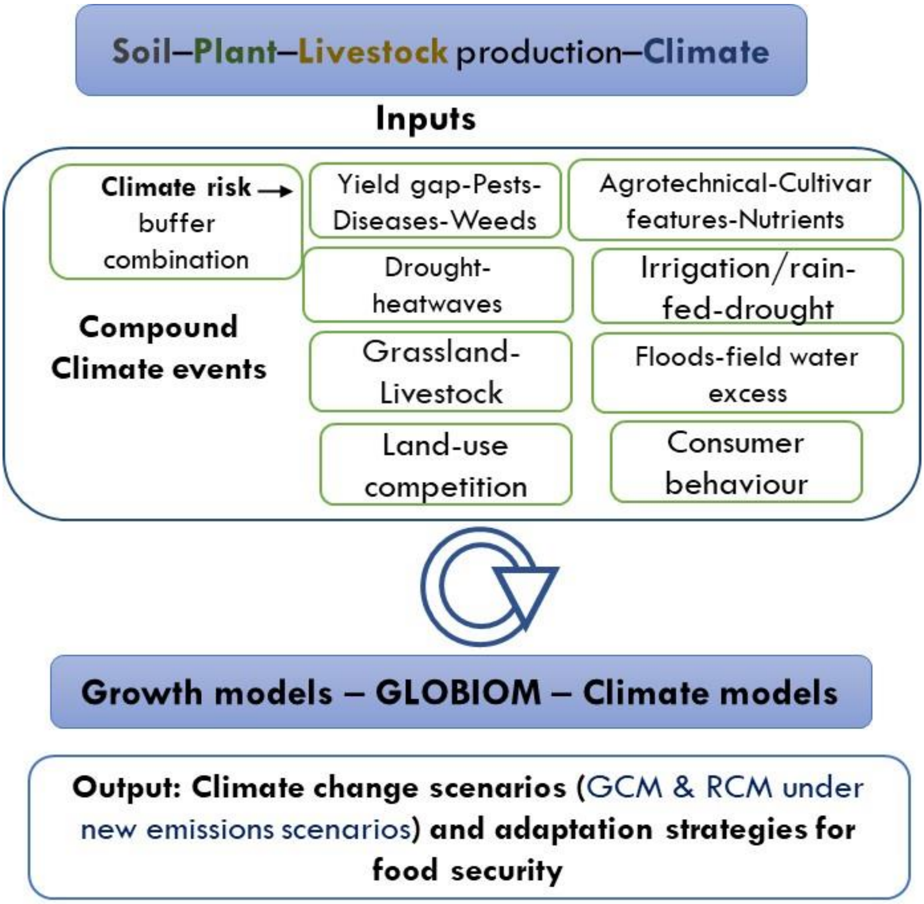

Fig. 8.7 Schematic interconnectivity of drivers of climate for food security using growth models, economic models and climate models

GLOBIOM-CZE

- it is a global partial equilibrium economic model adapted to the Czech agricultural context that integrates the land-use based sectors: agriculture including livestock, and forestry using a bottom-up approach for the supply side based on detailed spatial units information including land cover, land use, management system, and other biophysical and technical cost information (*CzechGlobe team*)
- it is grounded on the market equilibrium where maximizes the sum of producer and consumer surplus conditioned to resources, technological, demand, and policy constraints
- the demand for final products and the international trade is represented at 57 aggregated economic regions, where 28 corresponds to EU member states and UK, and 29 regions outside Europe
- the Czech Republic is characterized by its demand and trade flows

- it can trade with other countries in the EU and with regions outside the EU through a common EU hub market
- the biophysical process-based model Environmental Policy Integrated Climate (EPIC) computed the productivity, fertilizer, and irrigation demand
- EPIC also informs the grassland productivity
- the European crop sector is represented by crop rotations of 18 crops derived from crop shares calculated from EUROSTAT statistics based on crop areas at NUTS2 level using the crop rotation model CropRota

Modelling future scenarios of food resilience

When modelling future scenarios of food resilience, the most suitable approaches we can use the dynamic interconnectivity of growth models, economic models and climate models. An overview of the scenario development process is given in the Figure 8.7.

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Video Microsoft Stream

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CZECH REPUBLIC DEVELOPMENT COOPERATION

CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

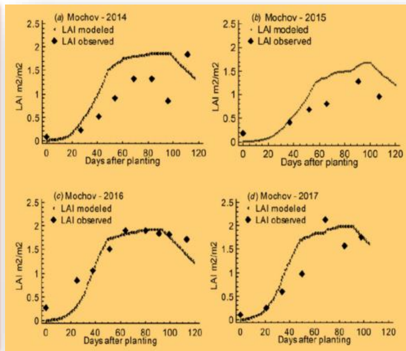
Ministry of Foreign Affairs of the Czech Republic

Chapter 9

Overview of the Decision Support System for Agrotechnology Transfer Crop Simulation Model

Keywords:

- crop model
- DSSAT (Decision Support System for Agrotechnology Transfer)
- weather data
- soil data
- crop management data
- cultivar
- plant growth
- yield



Chapter 9: Overview of the Decision Support System for Agrotechnology Transfer Crop Simulation Model

9.1 DSSAT model (Decision Support System for Agrotechnology Transfer)

- it is a software application program that comprises crop simulation models for over 42 crops as well as tools to facilitate effective use of the models
- the tools include database management programs for soil, weather, crop management and experimental data, utilities, and application programs
- the crop simulation models simulate growth, development, and yield as a function of the soil-plant-atmosphere dynamics
- the crop models require daily weather data, soil surface and profile information, and detailed crop management as input
- crop genetic information is defined in a crop species file that is provided by DSSAT and cultivar or variety information that should be provided by the user
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- at the end of each day, the plant and soil water, nitrogen, phosphorus, and carbon balances are updated, as well as the crop's vegetative and reproductive development stage

9.2 DSSAT Model Framework

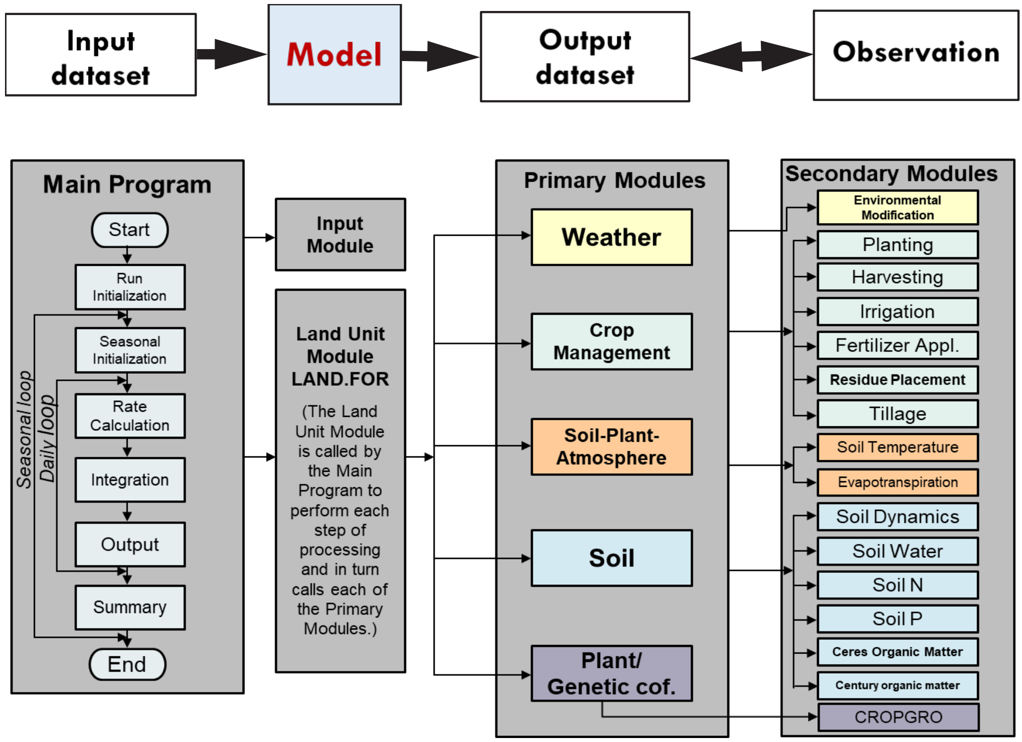
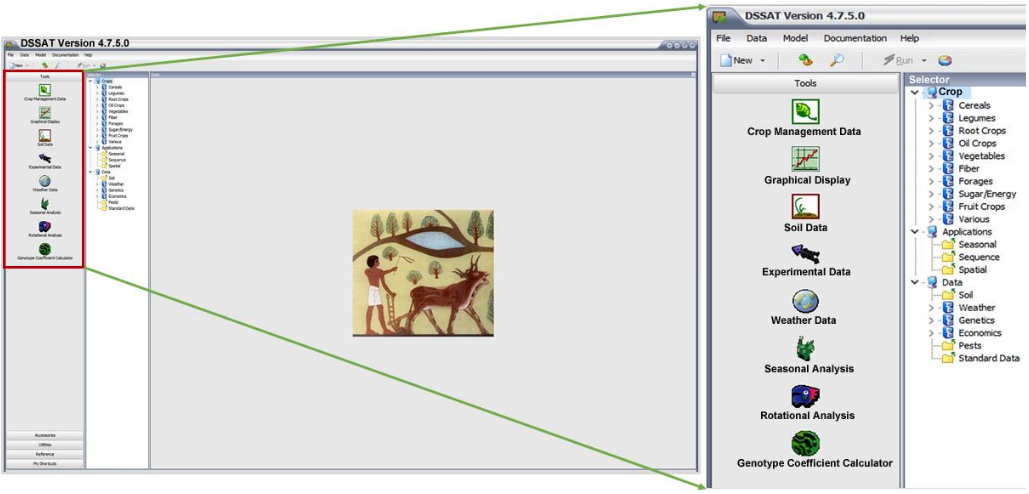


Fig. 9.1 Components and modular structure of DSSAT crop model

Source: Hoogenboom and Jones, 2010; Hoogenboom *et al.,* 2019

9.3 DSSAT Interface



9.3.1 Input Framework

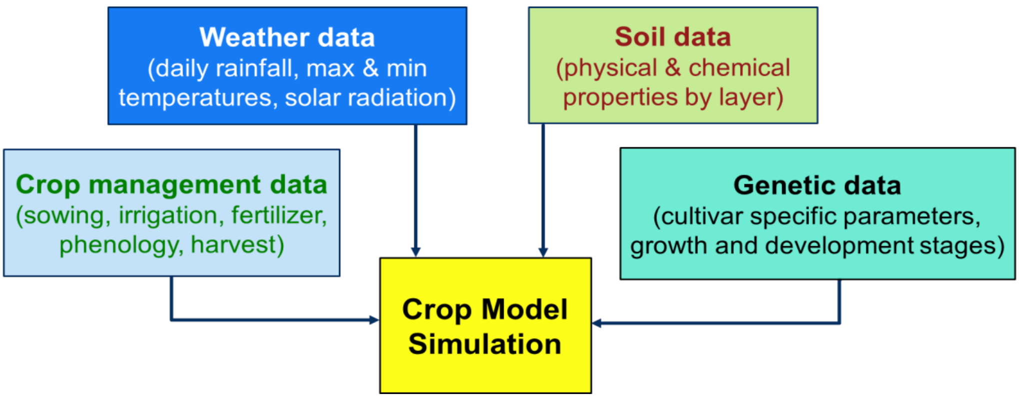


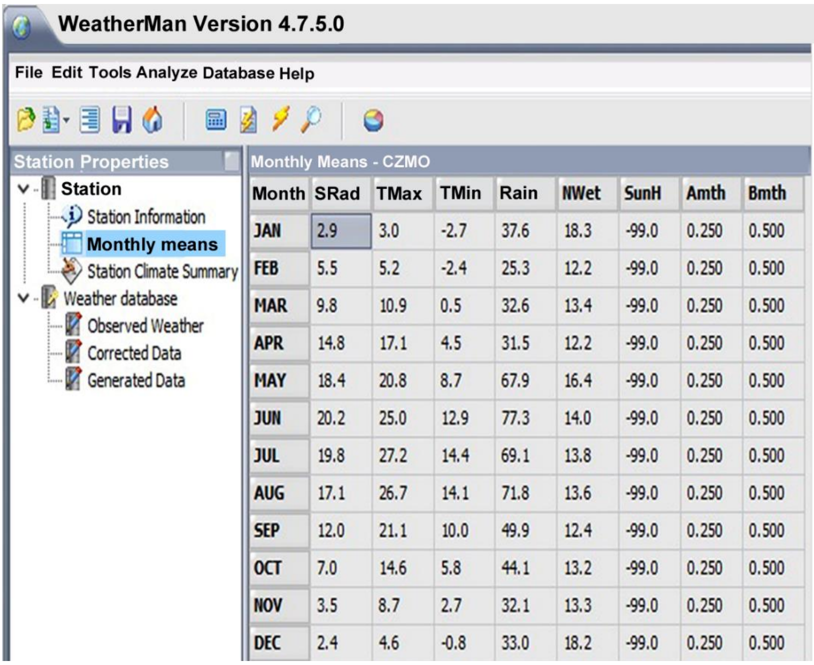
Fig 9.2 Input framework of the DSSAT model

Source: Hoogenboom and Jones, 2010; Hoogenboom *et al.,* 2019

9.3.2 Input Component of DSSAT

a) Weather component (WeatheMan)

This component of the simulation model deals with the weather station information, weather dataset management according to the DSSAT model prescribed format and naming convention



Month	SRad	TMax	TMin	Rain	NWet	SunH	Amth	Bmth
JAN	2.9	3.0	-2.7	37.6	18.3	-99.0	0.250	0.500
FEB	5.5	5.2	-2.4	25.3	12.2	-99.0	0.250	0.500
MAR	9.8	10.9	0.5	32.6	13.4	-99.0	0.250	0.500
APR	14.8	17.1	4.5	31.5	12.2	-99.0	0.250	0.500
MAY	18.4	20.8	8.7	67.9	16.4	-99.0	0.250	0.500
JUN	20.2	25.0	12.9	77.3	14.0	-99.0	0.250	0.500
JUL	19.8	27.2	14.4	69.1	13.8	-99.0	0.250	0.500
AUG	17.1	26.7	14.1	71.8	13.6	-99.0	0.250	0.500
SEP	12.0	21.1	10.0	49.9	12.4	-99.0	0.250	0.500
OCT	7.0	14.6	5.8	44.1	13.2	-99.0	0.250	0.500
NOV	3.5	8.7	2.7	32.1	13.3	-99.0	0.250	0.500
DEC	2.4	4.6	-0.8	33.0	18.2	-99.0	0.250	0.500

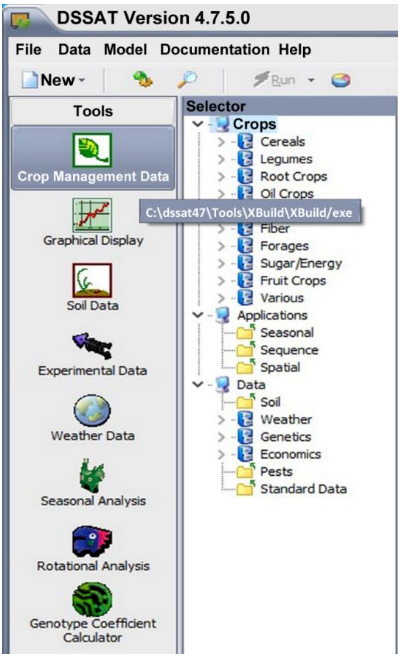
b) Soil component (SBuild)

The soil component of the model contains all the information about soil bio-physio-chemical properties depending on specific depth/layers.

Layer Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Organic Carbon (%)	pH in water	CEC (cmol kg-1)	Total nitrogen (%)	LL, Lower limit (cm^3 cm^{-3})	DUL, Upper limit drain (cm^3 cm^{-3})	BD, Bulk density (g cc^{-1})
10	24.1	58.2	-99	1.59	5.1	-99	0.1	-99	-99	1.31
20	23.2	58.6	-99	1.58	5.1	-99	0.13	-99	-99	1.32
30	22.7	59.6	-99	1.56	5.3	-99	0.12	-99	-99	1.31
40	24.3	59.1	-99	1.98	5.7	-99	0.1	-99	-99	1.39
50	24.1	59.3	-99	1.97	5.8	-99	0.1	-99	-99	1.34
60	23.9	60.1	-99	1.93	5.9	-99	0.12	-99	-99	1.38
70	23.4	59.8	-99	1.49	6.3	-99	0.13	-99	-99	1.43
80	22.3	60.1	-99	1.44	6.4	-99	0.14	-99	-99	1.41
90	21.5	60.2	-99	1.42	6.5	-99	0.12	-99	-99	1.39

c) Crop management component (XBuild)

The crop management component deals with all necessary information of crop and production management. From land preparation till harvesting, all information on crop production, fertilizer management, irrigation, intercultural operations etc. is collected and incorporated into this component.



d) Cultivar Coefficient component (Variety specific genetic information)

This component contains the information of specific crop varieties. e.g., development of different growth stages, emergence, leaf initiation, flowering, bud formation, maturity, harvesting, yield, and biomass

TMGRO047 - Notepad
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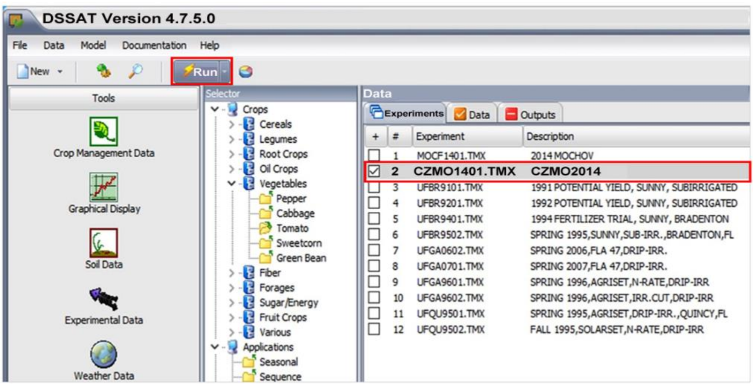
```
*TOMATO CULTIVAR COEFFICIENTS: CRGRO047 MODEL
!
! PARAM    DEFINITIONS
! =====    ===========
! EXPNO    Number of experiments used to estimate cultivar parameters
! ECO#     Code for the ecotype to which this cultivar belongs (see *.eco file)
! CSDL     Critical Short Day Length below which reproductive development
!          progresses with no daylength effect (for shortday plants) (hour)
! PPSEN    Slope of the relative response of development to photoperiod with time
!          (positive for shortday plants) (1/hour)
! EM-FL    Time between plant emergence and flower appearance (R1)
!          (photothermal days)
! FL-SH    Time between first flower and first pod (R3) (photothermal days)
! FL-SD    Time between first flower and first seed (R5) (photothermal days)
! SD-PM    Time between first seed (R5) and physiological maturity (R7)
!          (photothermal days)
! FL-LF    Time between first flower (R1) and end of leaf expansion
!          (photothermal days)
! LFMAX    Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light
!          (mg CO2/m2-s)
! SLAVR    Specific leaf area of cultivar under standard growth conditions
!          (cm2/g)
! SIZLF    Maximum size of full leaf (three leaflets) (cm2)
! XFRT     Maximum fraction of daily growth that is partitioned to seed + shell
! WTPSD    Maximum weight per seed (g)
! SFDUR    Seed filling duration for pod cohort at standard growth conditions
!          (photothermal days)
! SDPDV    Average seed per pod under standard growing conditions (#/pod)
! PODUR    Time required for cultivar to reach final pod load under optimal
!          conditions (photothermal days)
! THRSH    Threshing percentage. The maximum ratio of (seed/(seed+shell))
!          at maturity. Causes seed to stop growing as their dry weight
!          increases until the shells are filled in a cohort.
! SDPRO    Fraction protein in seeds (g(protein)/g(seed))
! SDLP     Fraction oil in seeds (g(oil)/g(seed))
```

9.4 Operational Framework – DSSAT (e.g., Tomato, Variety-Thomas F1, Mochov-2014)



9.5 Output Framework

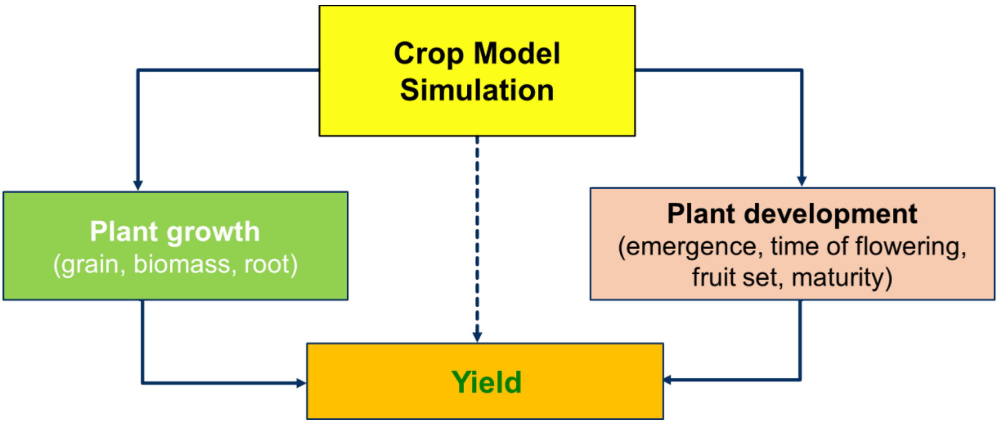
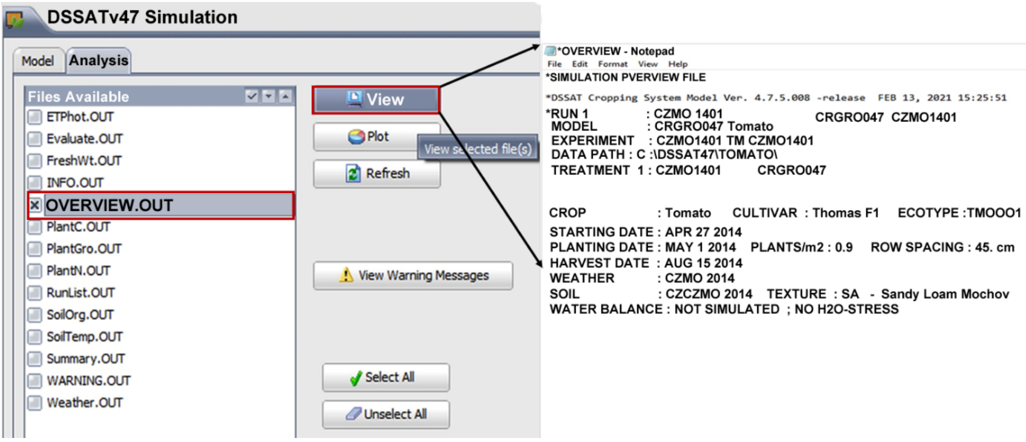
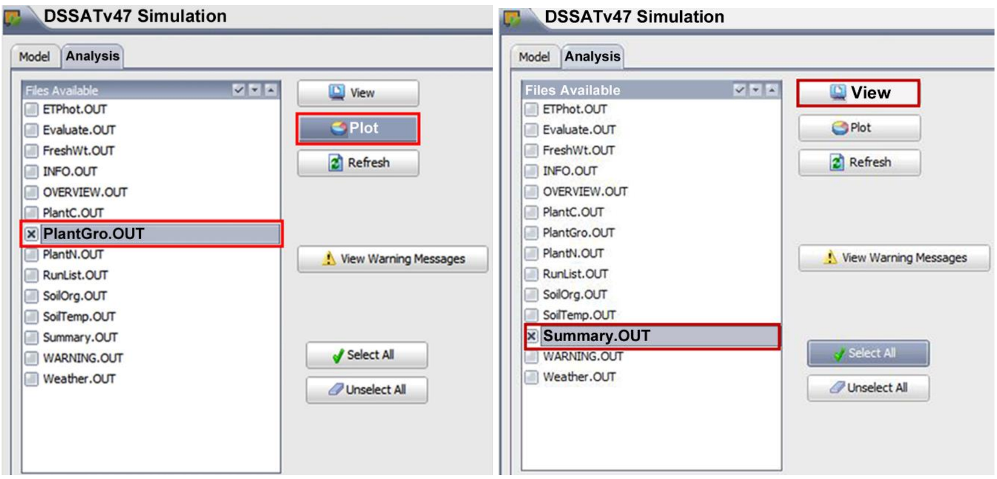


Fig. 9.3 Output framework of the DSSAT model

Source: Hoogenboom and Jones, 2010; Hoogenboom *et al.*, 2019

9.5.1 Output Component of DSSAT





***Summary - Notepad**

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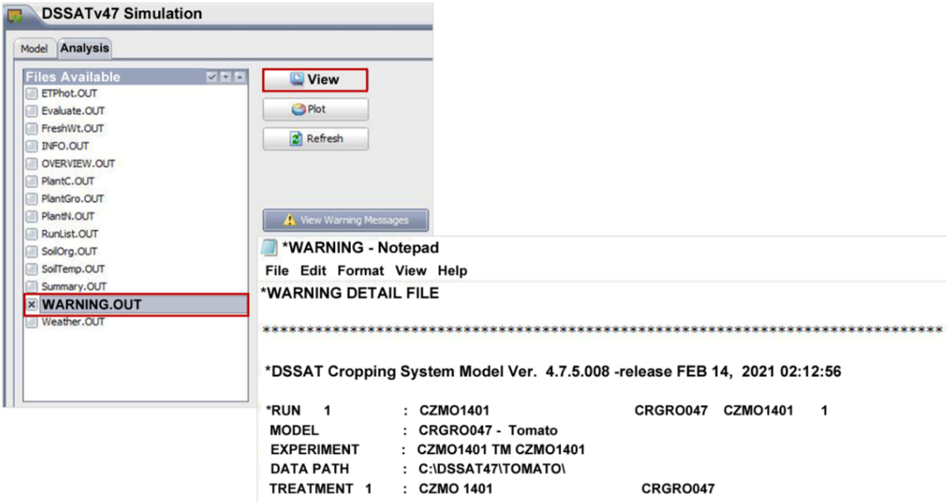
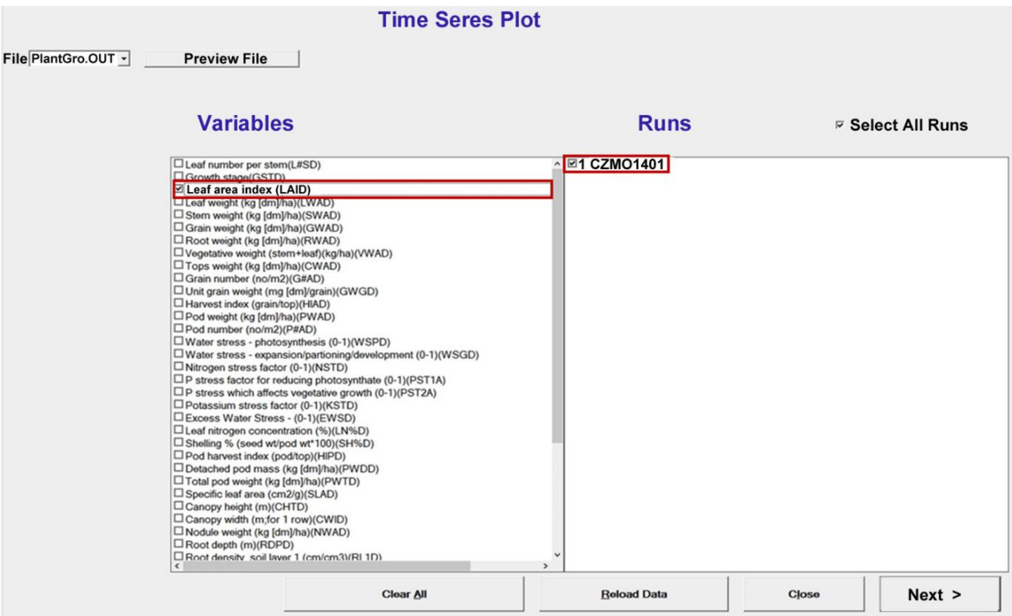
***SUMMARY : CZMO1401TM CZMO2014 DSSAT Cropping System Model Ver. 4.7.5.608 -release FEB 14, 2021; 62:12:56**

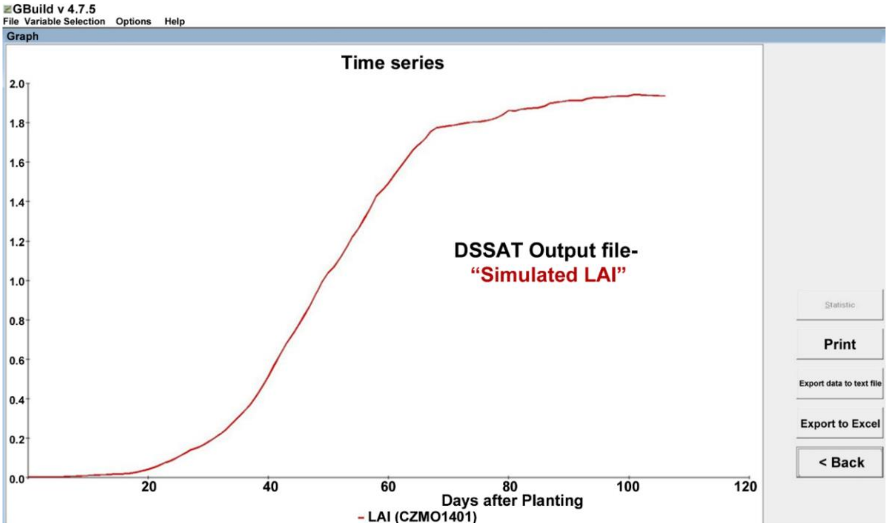
!IDENTIFIERS.......EXPERIMENT AND TREATMENT… SITE INFORMATION............ DATES........... DRY WEIGHT, YIELD AND YIELD COMPONENTS....

```
@ RUNNO TRNO R# 0# P# CR MODEL...    EXNAME.. TNAM.....  FNAH.... WSTA.... SOIL_ID.. SDAT PDAT EDAT ADAT  MDAT  HDAT  DWAP  CWAM  HWAM  HWAH BWAH  PWAM
      1    1    1 0  1   TM CRGRO047 CZMO1401 CZMO 1401 CZM01401 CZM02014 CZM02014 2014117 2014121 -99  2014156  2614276  2614327 8  5050 2050 3723  0  3060
```



9.5.2 Graphical Output Component of DSSAT (Plots)





9.6 Model Calibration and Evaluation

- the crop model calibration will be performed by comparing the observed and simulated values to confirm the acceptable estimates of the model outputs
- two statistical criteria will be used to evaluate the model: the root mean square error (RMSE) and the normalized root mean square error (NRMSE)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \qquad (1)$$

$$\text{NRMSE} = 100\,\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}}{\text{Omax} - \text{Omin}} \qquad (2)$$

where, *S* are the simulated values, O are the observed values and n are the number of data points. Omax and Omin are the maximum and minimum values of the observations respectively.

Ch9 Sources:

- Potopová, V. (2021). Study materials published on Moodle – teaching system for teaching support at the Czech University of Life Sciences in Prague. Available from https://moodle.czu.cz/. Lecture 9: Overview of the Decision Support System for Agrotechnology Transfer Crop Simulation Model.

Video Microsoft Stream

Additional sources:

- Hoogenboom, G., Jones, J. W., Wilkens, P. W., Porter, C. H., Boote, K. J., Hunt, L. A., ... & Tsuji, G. Y. (2010). Decision support system for agrotechnology transfer version 4.5 [CD]. *Univ. of Hawaii, Honolulu*, Hawaii.
- Hoogenboom, G., Porter, C. H., Boote, K. J., Shelia, V., Wilkens, P. W., Singh, U., ... & Jones, J. W. (2019). Advances in crop modeling for a sustainable agriculture. *The DSSAT Crop Modeling Ecosystem*, 173-216.

Chapter 10

Application of DSSAT Crop Simulation Model

Keywords:

- components of DSSAT crop model
- minimum dataset
- SBuild
- WeatherMan
- XBuild
- acronyms

Chapter 10: Application of DSSAT Crop Simulation Model

10.1 Soil component in DSSAT

10.1.1 Soil Data Inputs and Utilities

- Minimum soil data
  - Soil physical data
    - ✓ soil layer depth (cm)
    - ✓ clay (%)
    - ✓ silt (%)
    - ✓ sand (%)
    - ✓ BD, bulk density (g cc^{-1})
    - ✓ LL, lower limit (cm^3 cm^{-3})
    - ✓ DUL, upper limit drain (cm^3 cm^{-3})
  - Soil Chemical data
    - organic carbon (%)
    - pH in water
    - CEC, cation exchange capacity (cmol kg^{-1})
    - total nitrogen (%)

- Site observations
    - latitude (degrees decimals)
    - longitude (degrees decimals)
    - elevation (m a.s.l.)

- Collection of soil dataset
    - soil data can be collected by field soil collection and laboratory analysis from the specific experimental sites

Fig. 10.1 Soil sample collection instruments

- File naming convention
  - AABBNNnn.SOL
    - ✓ AA = Institute Identifier (ID)
    - ✓ BB = Site ID
    - ✓ NN = Year of observation

For example:

  - CZMO2014.SOL
    - ✓ CZ = Česká zemědělská univerzita v Praze (Institute ID)
    - ✓ MO = Mochov (Site ID)
    - ✓ 2014 = 2014 (Year of observation)

- Soil File Structure and Header

```
*CZMO2014  Soil Survey SIL        90  Sandy Loam Mochov
@SITE        COUNTRY          LAT     LONG  SCS FAMILY
 Mochov      Czechia         50.08   14.47  Sandy Loam
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   .25    76   -99     1 IB001 IB001 IB001
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB  SCEC  SADC
    10   -99   .19  .391  .469     1   .68  1.31  1.59  24.1  58.2   -99    .1   5.1   -99   -99   -99
    20   -99  .185  .386  .465     1   .68  1.32  1.58  23.2  58.6   -99   .13   5.1   -99   -99   -99
    30   -99  .182  .384  .469  .607   .68  1.31  1.56  22.7  59.6   -99   .12   5.3   -99   -99   -99
    40   -99  .201  .414  .437  .497   .68  1.39  1.98  24.3  59.1   -99    .1   5.7   -99   -99   -99
    50   -99    .2  .413  .455  .407   .68  1.34  1.97  24.1  59.3   -99    .1   5.8   -99   -99   -99
    60   -99  .198  .411  .441  .333   .68  1.38  1.93  23.9  60.1   -99   .12   5.9   -99   -99   -99
    70   -99  .184  .385  .426  .273   .68  1.43  1.49  23.4  59.8   -99   .13   6.3   -99   -99   -99
    80   -99  .177  .377  .433  .223   .68  1.41  1.44  22.3  60.1   -99   .14   6.4   -99   -99   -99
    90   -99  .172  .372  .441  .183   .68  1.39  1.42  21.5  60.2   -99   .12   6.5   -99   -99   -99
```

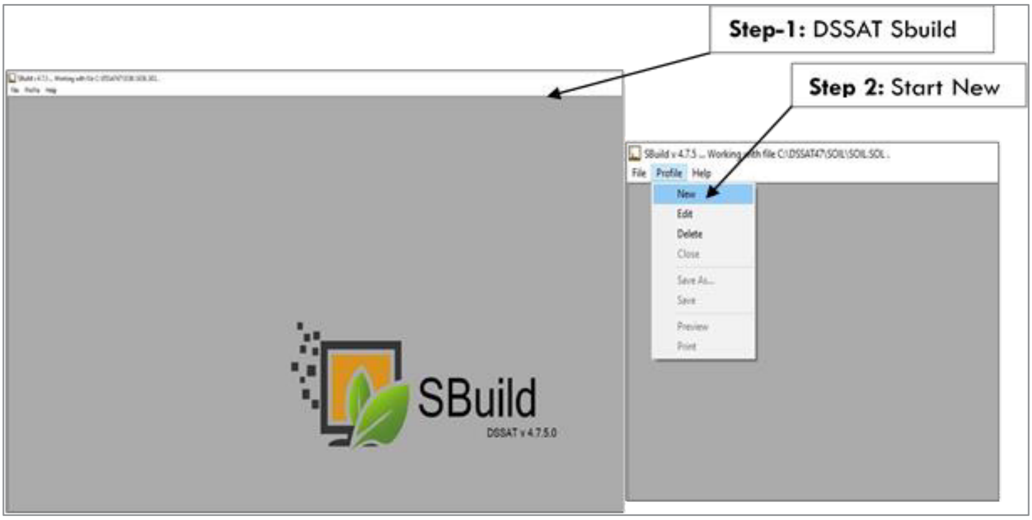
- Data quality
  - missing data (any missing data in DSSAT is called (-99)
  - erroneous data
    - ✓ water holding capacity < Saturation capacity
    - ✓ fertility factor (<0 or >1)

10.1.2 Soil Module – DSSAT (SBuild)

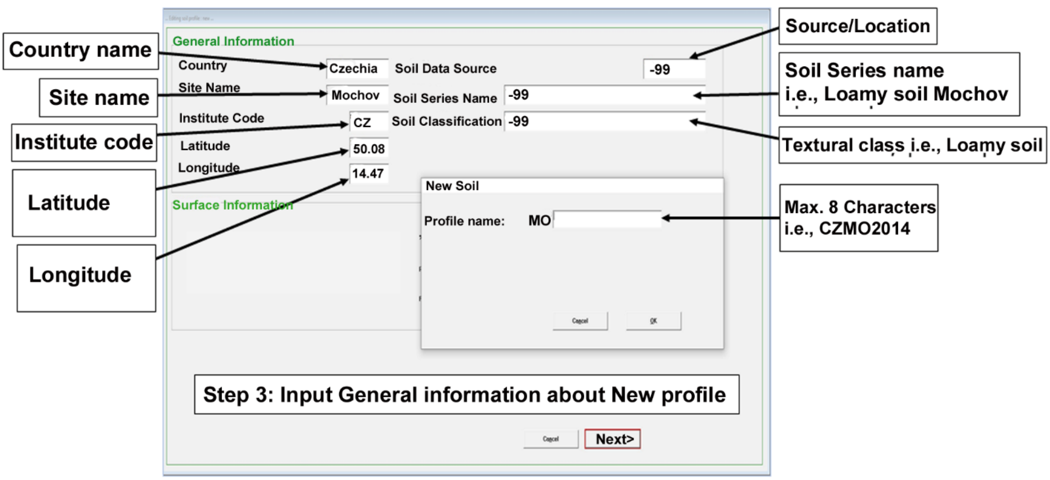
- soil management utility program
- import dataset
- export data in DSSAT format
- fill missing data

Data is stored in a database and exported into DSSAT soil files

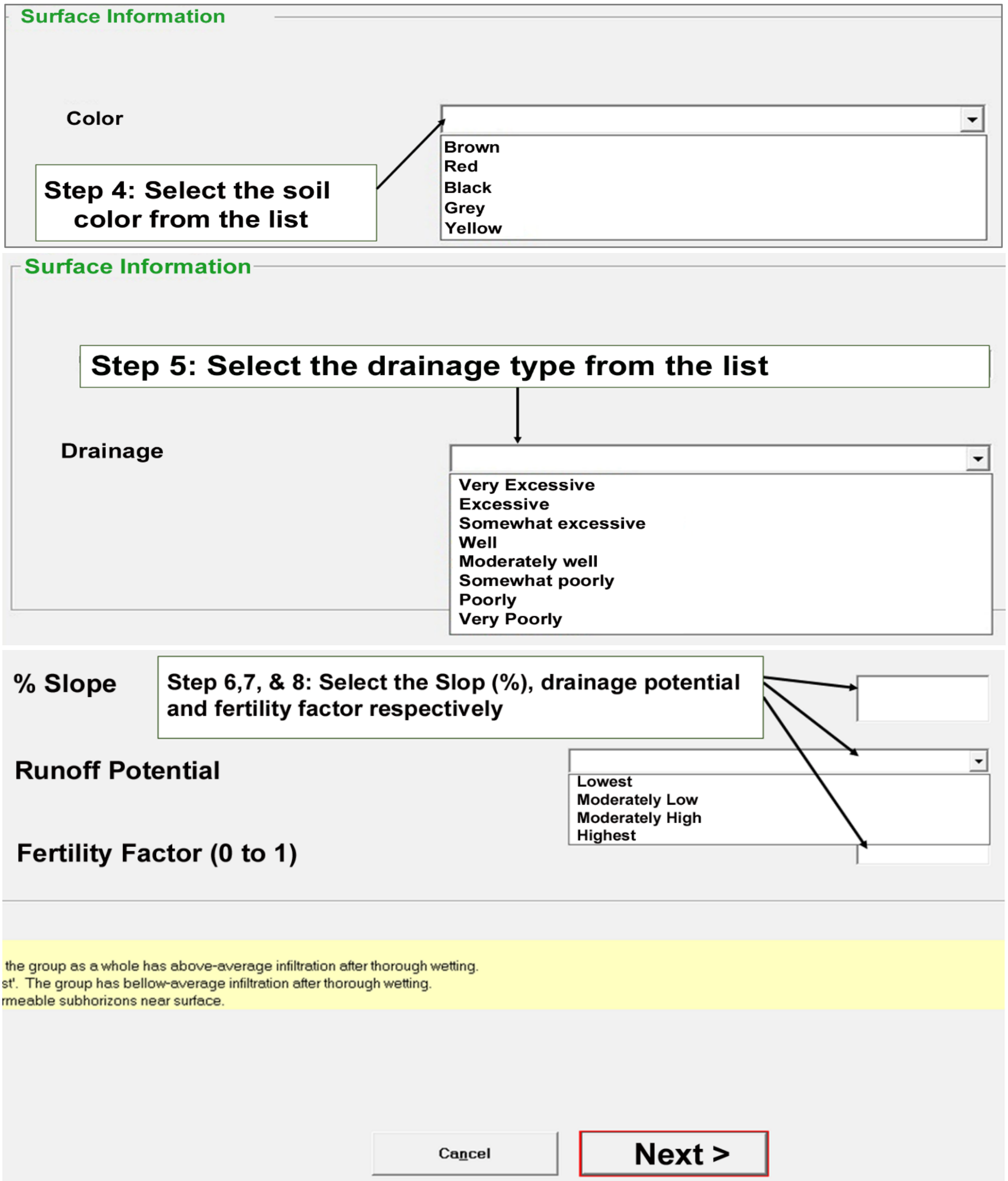
- SBuild- Basic Information

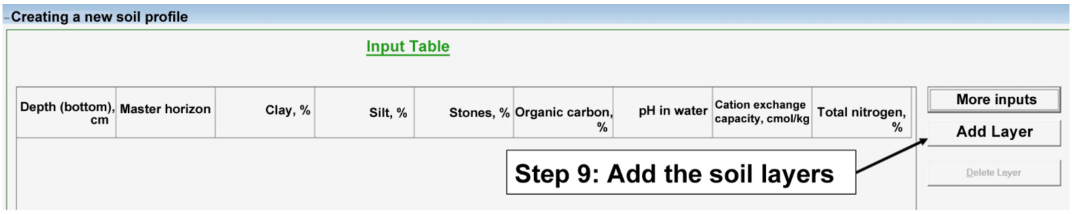


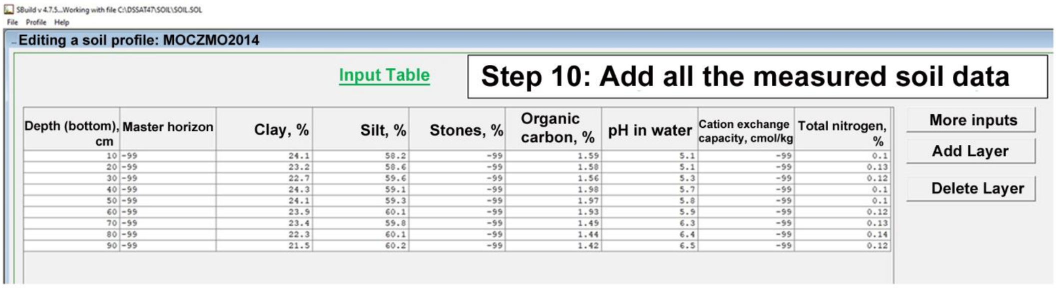
- SBuild- Interface



- SBuild- Data Input

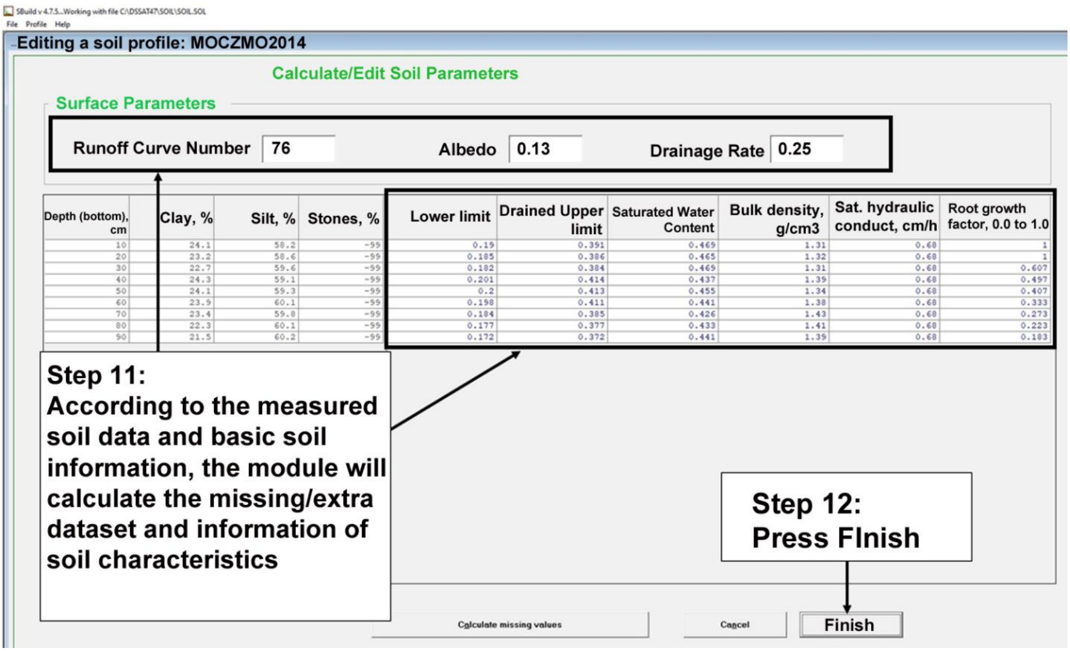






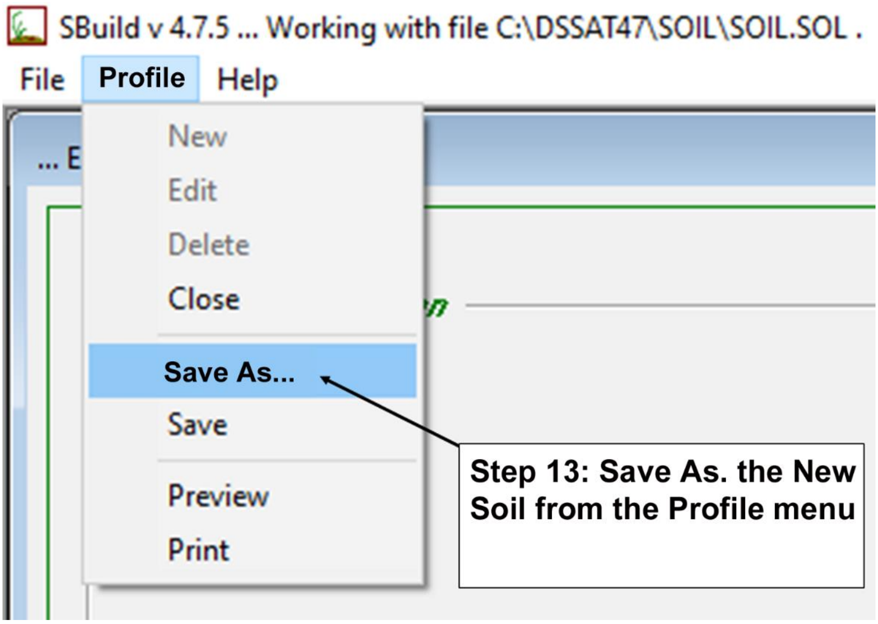
Depth (bottom), cm	Master horizon	Clay, %	Silt, %	Stones, %	Organic carbon, %	pH in water	Cation exchange capacity, cmol/kg	Total nitrogen, %
10	-99	24.1	58.2	-99	1.59	5.1	-99	0.1
20	-99	23.2	58.6	-99	1.58	5.1	-99	0.13
30	-99	22.7	59.6	-99	1.56	5.3	-99	0.12
40	-99	24.3	59.1	-99	1.98	5.7	-99	0.1
50	-99	24.1	59.3	-99	1.97	5.8	-99	0.1
60	-99	23.9	60.1	-99	1.93	5.9	-99	0.12
70	-99	23.4	59.8	-99	1.49	6.3	-99	0.13
80	-99	22.3	60.1	-99	1.44	6.4	-99	0.14
90	-99	21.5	60.2	-99	1.42	6.5	-99	0.12

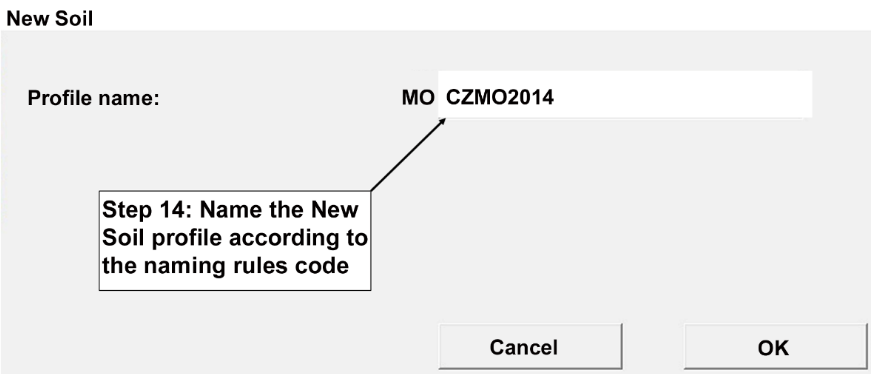
- Missing/Extra Data - Calculation

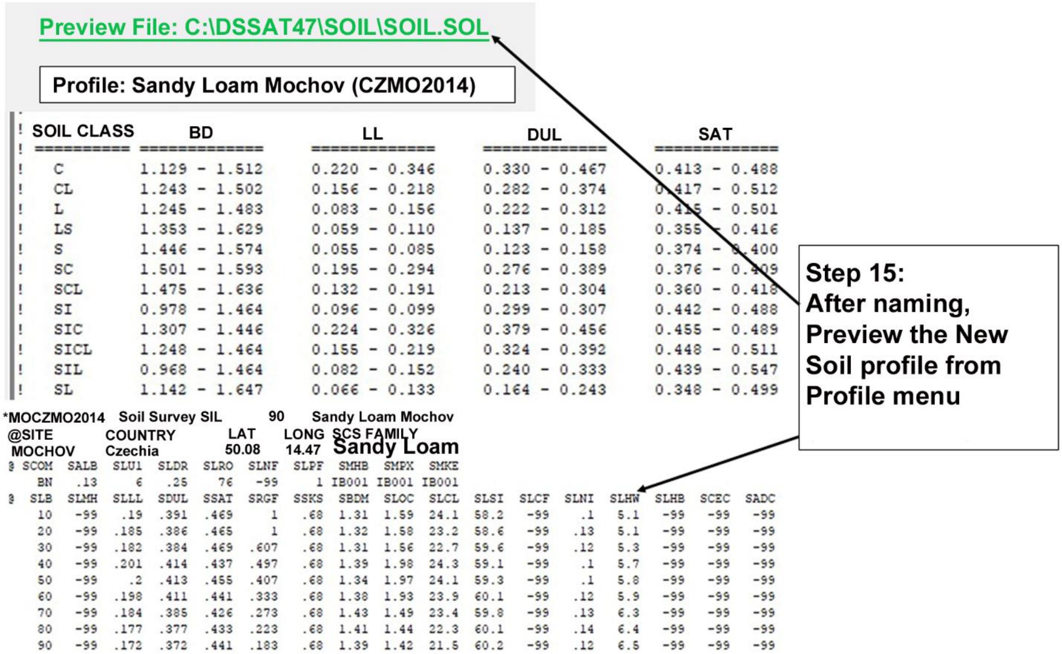


Depth (bottom), cm	Clay, %	Silt, %	Stones, %	Lower limit	Drained Upper limit	Saturated Water Content	Bulk density, g/cm3	Sat. hydraulic conduct, cm/h	Root growth factor, 0.0 to 1.0
10	24.1	58.2	-99	0.19	0.391	0.469	1.31	0.68	1
20	23.2	58.6	-99	0.185	0.386	0.465	1.32	0.68	1
30	22.7	59.6	-99	0.182	0.384	0.469	1.31	0.68	0.607
40	24.3	59.1	-99	0.201	0.414	0.437	1.39	0.68	0.497
50	24.1	59.3	-99	0.2	0.413	0.455	1.34	0.68	0.407
60	23.9	60.1	-99	0.198	0.411	0.441	1.38	0.68	0.333
70	23.4	59.8	-99	0.184	0.385	0.426	1.43	0.68	0.273
80	22.3	60.1	-99	0.177	0.377	0.433	1.41	0.68	0.223
90	21.5	60.2	-99	0.172	0.372	0.441	1.39	0.68	0.183

- Saving the New Soil profile





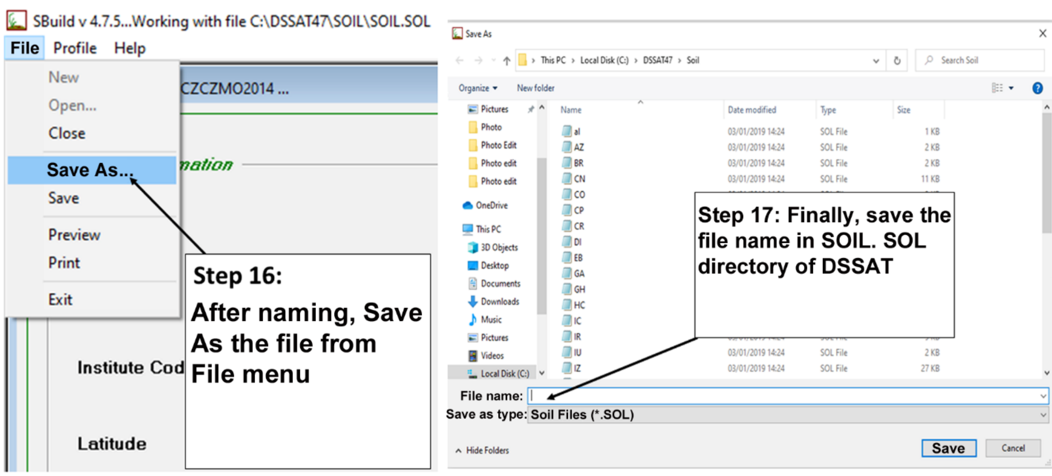


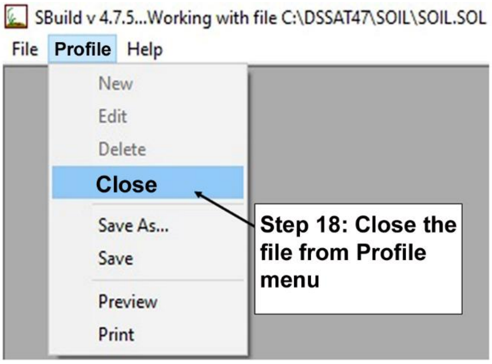
Preview File: C:\DSSAT47\SOIL\SOIL.SOL

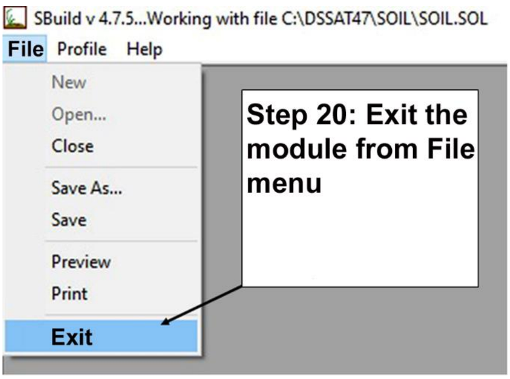
Profile: Sandy Loam Mochov (CZMO2014)

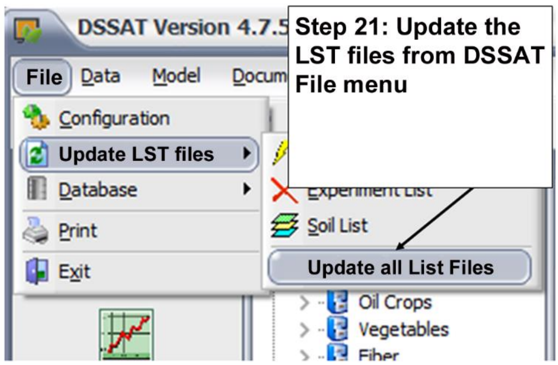
SOIL CLASS	BD	LL	DUL	SAT
C	1.129 - 1.512	0.220 - 0.346	0.330 - 0.467	0.413 - 0.488
CL	1.243 - 1.502	0.156 - 0.218	0.282 - 0.374	0.417 - 0.512
L	1.245 - 1.483	0.083 - 0.156	0.222 - 0.312	0.415 - 0.501
LS	1.353 - 1.629	0.059 - 0.110	0.137 - 0.185	0.355 - 0.416
S	1.446 - 1.574	0.055 - 0.085	0.123 - 0.158	0.374 - 0.400
SC	1.501 - 1.593	0.195 - 0.294	0.276 - 0.389	0.376 - 0.409
SCL	1.475 - 1.636	0.132 - 0.191	0.213 - 0.304	0.360 - 0.418
SI	0.978 - 1.464	0.096 - 0.099	0.299 - 0.307	0.442 - 0.488
SIC	1.307 - 1.446	0.224 - 0.326	0.379 - 0.456	0.455 - 0.489
SICL	1.248 - 1.464	0.155 - 0.219	0.324 - 0.392	0.448 - 0.511
SIL	0.968 - 1.464	0.082 - 0.152	0.240 - 0.333	0.439 - 0.547
SL	1.142 - 1.647	0.066 - 0.133	0.164 - 0.243	0.348 - 0.499

```
*MOCZMO2014   Soil Survey SIL       90     Sandy Loam Mochov
@SITE         COUNTRY          LAT     LONG  SCS FAMILY
 MOCHOV       Czechia          50.08   14.47 Sandy Loam
@ SCOM  SALB  SLU1  SLDR  SLRO  SLNF  SLPF  SMHB  SMPX  SMKE
    BN   .13     6   .25    76   -99     1 IB001 IB001 IB001
@  SLB  SLMH  SLLL  SDUL  SSAT  SRGF  SSKS  SBDM  SLOC  SLCL  SLSI  SLCF  SLNI  SLHW  SLHB  SCEC  SADC
    10   -99   .19  .391  .469     1   .68  1.31  1.59  24.1  58.2   -99    .1   5.1   -99   -99   -99
    20   -99  .185  .386  .465     1   .68  1.32  1.58  23.2  58.6   -99   .13   5.1   -99   -99   -99
    30   -99  .182  .384  .469  .607   .68  1.31  1.56  22.7  59.6   -99   .12   5.3   -99   -99   -99
    40   -99  .201  .414  .437  .497   .68  1.39  1.98  24.3  59.1   -99    .1   5.7   -99   -99   -99
    50   -99    .2  .413  .455  .407   .68  1.34  1.97  24.1  59.3   -99    .1   5.8   -99   -99   -99
    60   -99  .198  .411  .441  .333   .68  1.38  1.93  23.9  60.1   -99   .12   5.9   -99   -99   -99
    70   -99  .184  .385  .426  .273   .68  1.43  1.49  23.4  59.8   -99   .13   6.3   -99   -99   -99
    80   -99  .177  .377  .433  .223   .68  1.41  1.44  22.3  60.1   -99   .14   6.4   -99   -99   -99
    90   -99  .172  .372  .441  .183   .68  1.39  1.42  21.5  60.2   -99   .12   6.5   -99   -99   -99
```







10.2 Weather Component in DSSAT

10.2.1 Weather Data Inputs and Utilities

- Weather Dataset
  - minimum dataset
  - weather file structure
  - WeatherMan

- Minimum weather data
  - Daily Observations
    - ✓ maximum temperature (°C)
    - ✓ minimum temperature (°C)
    - ✓ solar radiation (MJ m^{-2} day^{-1})
    - ✓ precipitation (mm)
  - Site Observations
    - ✓ latitude (degree decimals)
    - ✓ longitude (degree decimals)

- ✓ elevation (m a.s.l.)
- ✓ long-term average temperature (°C)
- ✓ amplitude of warmest and coolest monthly long-term average temperature (°C)
- ✓ temperature sensor height (m, above ground)

- Collection of weather dataset
  - minimum set of data can be easily collected by experimentalists from the weather observation stations

Fig. 10.2 Sample of the professional automatic and manual weather stations

- File naming convention
  - AABBNNnn.WTH
    - ✓ AA = Institute Identifier (ID)
    - ✓ BB = Site ID
    - ✓ NN = Year of observation

for example:

  - CZMO1401.WTH
    - ✓ CZ = Česká zemědělská univerzita v Praze
    - ✓ MO = Mochov
    - ✓ 1401 = 2014 (expt. no. 01)
- Weather File Structure

```
*WEATHER DATA : CZMO, MOCHOV, Czech Republic

@ INSI    LAT      LONG   ELEV  TAV   AMP
  CZMO  50.133  14.783  189   10.5  20.7

@DATE  SRAD  TMAX  TMIN  RAIN
 14001  1.9   5.3   0.4   0.0
 14002  1.9   5.0  -0.8   0.9
 14003  4.4   6.3  -2.0   0.0
 14004  1.9   7.2  -0.5   3.1
 14005  2.0   7.3   2.1   5.0
 14006  5.3   7.9  -0.8   0.0
 14007  4.2  10.1   1.7   0.0
 14008  3.8  12.4   1.1   0.1
 14009  2.0   9.0   1.6   1.1
 14010  4.0  10.7   4.1   0.0
```

10.3 Weather Module – DSSAT (WeatherMan)

- weather management utility program
- import dataset
- export data in DSSAT format
- fill missing data
- generate stochastic weather dataset

- Data quality
  - missing data (any missing data in DSSAT is called (-99)
  - erroneous data
    - ✓ rain < 0.0

- ✓ radiation =< 0.0
- ✓ Tmax < Tmin
- ✓ Tmax > Extreme_max

- Weather Generators
  - generate daily weather variables for maximum and minimum temperature, solar radiation, and precipitation
  - climate data as input
  - climate file (01 file per site)
    - ➢ AABB.*CLI*
      - ✓ AA = Institute ID
      - ✓ BB = Site ID

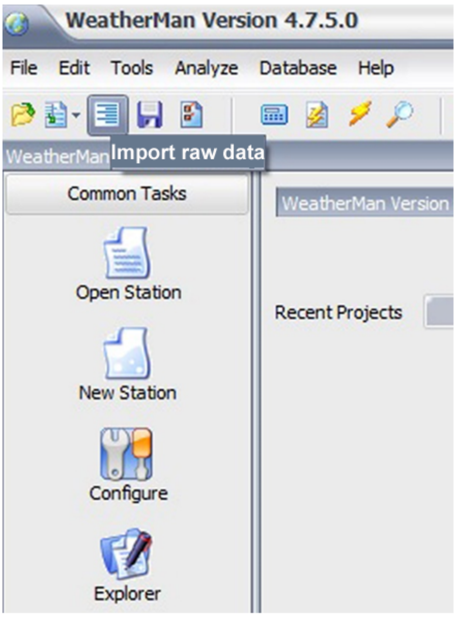
- Weather File Header

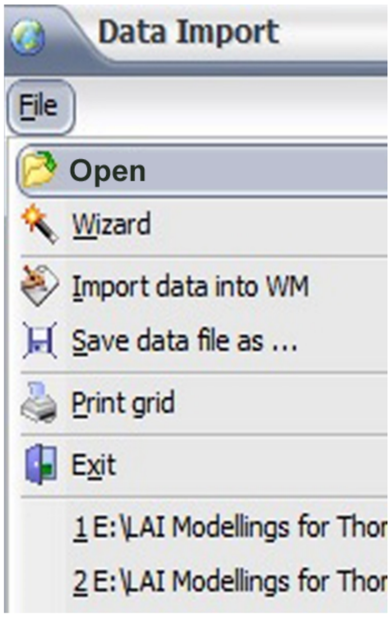
```
*CLIMATE: CZMO

@INSI  LAT     LONG    ELEV  TAV   AMP   SRAY  TMXY  TMNY  RAIY
 CZMO  50.133  14.783  189   10.5  20.7  11.1  15.4  5.6   572

@START  DURN  ANGA  ANGB  REFHT  WNDHT  SOURCE
  2010  10    0.25  0.50  -99.0  -99.0  Calculated_from_daily_data

@ GSST  GSDU
     1   365
```

10.3.1 Data Input – Monthly Averages

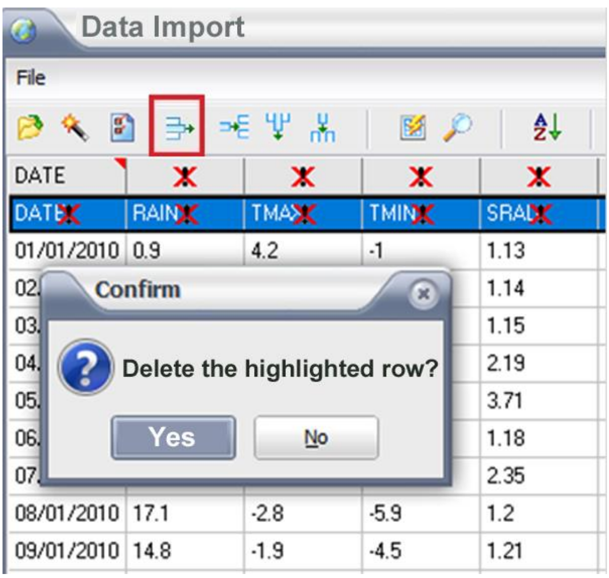
@Month	SRad	TMax	TMin	Rain	NWet	SunH	Amth	Bmth
JAN	2.9	3.0	-2.7	37.6	18.3	-99.0	0.250	0.500
FEB	5.5	5.2	-2.4	25.3	12.2	-99.0	0.250	0.500
MAR	9.8	10.9	0.5	32.6	13.4	-99.0	0.250	0.500
APR	14.8	17.1	4.5	31.5	12.2	-99.0	0.250	0.500
MAY	18.4	20.8	8.7	67.9	16.4	-99.0	0.250	0.500
JUN	20.2	25.0	12.9	77.3	14.0	-99.0	0.250	0.500
JUL	19.8	27.2	14.4	69.1	13.8	-99.0	0.250	0.500
AUG	17.1	26.7	14.1	71.8	13.6	-99.0	0.250	0.500
SEP	12.0	21.1	10.0	49.9	12.4	-99.0	0.250	0.500
OCT	7.0	14.6	5.8	44.1	13.2	-99.0	0.250	0.500
NOV	3.5	8.7	2.7	32.1	13.3	-99.0	0.250	0.500
DEC	2.4	4.6	-0.8	33.0	18.2	-99.0	0.250	0.500

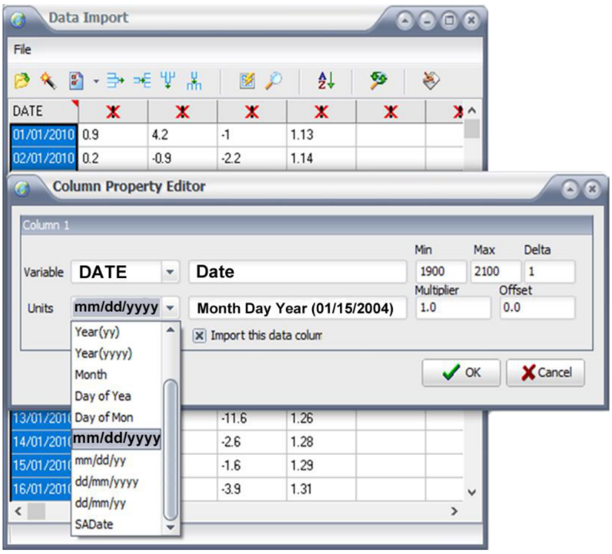
- WeatherMan – Detail
    - import from text, CSV, XLS, or DBF files
    - data is stored in a database and exported into DSSAT weather files

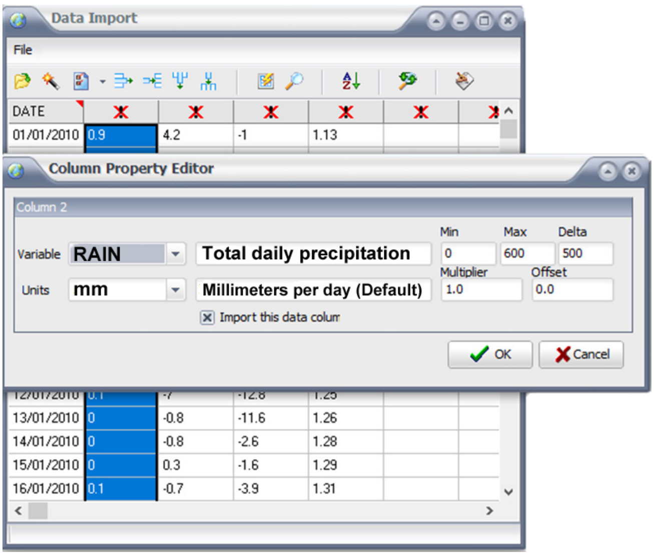


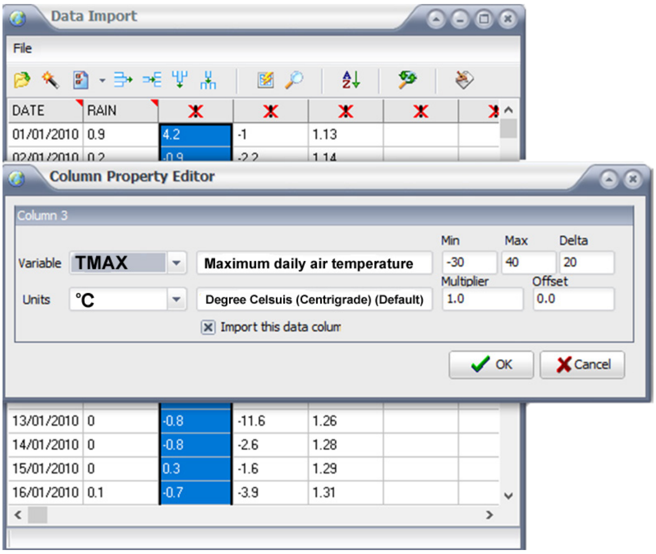


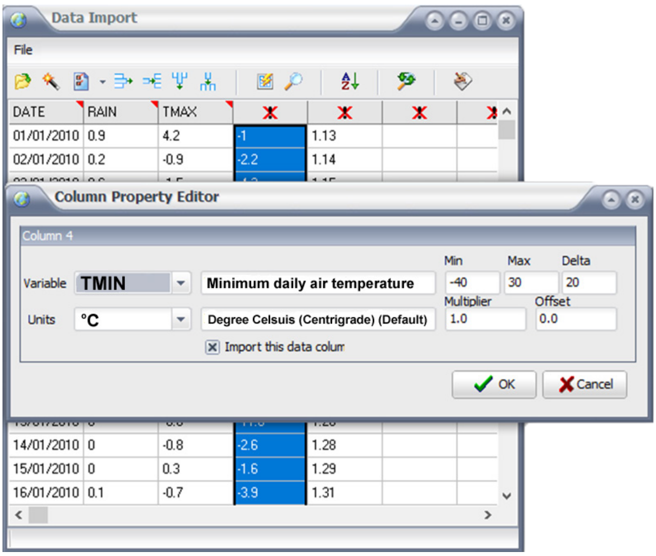
- Renaming the weather parameter "Headings"

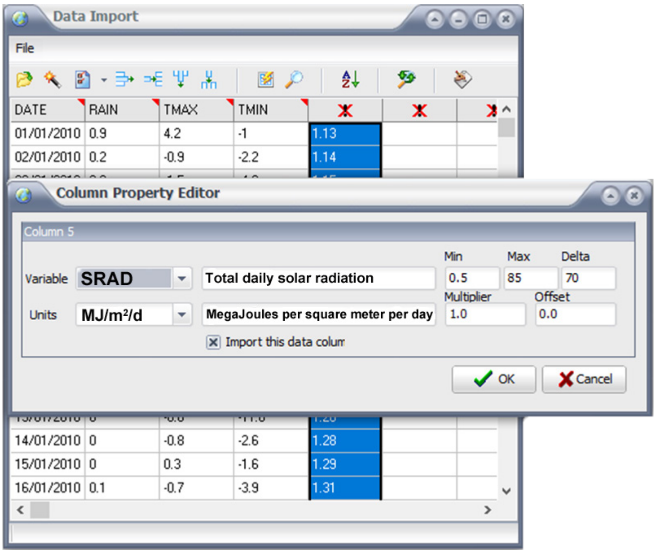



Data Import
File
DATE
01/01/2010 0.9 4.2 -1 1.13
02/01/2010 0.2 -0.9 -2.2 1.14
Column Property Editor
Column 1
Min Max Delta
Variable DATE Date 1900 2100 1
Units mm/dd/yyyy Month Day Year (01/15/2004)
Multiplier Offset
1.0 0.0
Import this data colum
OK
Cancel
Year(yy)
Year(yyyy)
Month
Day of Yea
Day of Mon
mm/dd/yyyy
mm/dd/yy
dd/mm/yyyy
dd/mm/yy
SADate
-11.6 1.26
-2.6 1.28
-1.6 1.29
-3.9 1.31

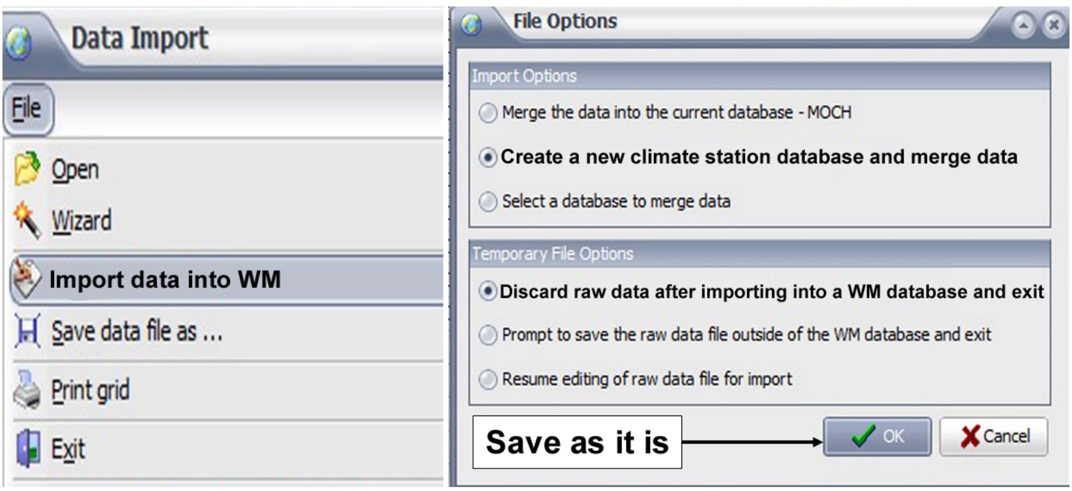

Data Import
File
DATE
01/01/2010 0.9 4.2 -1 1.13
Column Property Editor
Column 2
Min Max Delta
Variable RAIN Total daily precipitation 0 600 500
Units mm Millimeters per day (Default)
Multiplier Offset
1.0 0.0
Import this data colum
OK
Cancel
13/01/2010 0 -0.8 -11.6 1.26
14/01/2010 0 -0.8 -2.6 1.28
15/01/2010 0 0.3 -1.6 1.29
16/01/2010 0.1 -0.7 -3.9 1.31


Data Import
File
DATE
RAIN
01/01/2010
0.9
4.2
-1
1.13
Column Property Editor
Column 3
Variable
TMAX
Maximum daily air temperature
Min
Max
Delta
-30
40
20
Units
°C
Degree Celsius (Centrigrade) (Default)
Multiplier
Offset
1.0
0.0
Import this data colum
OK
Cancel
13/01/2010
0
-0.8
-11.6
1.26
14/01/2010
0
-0.8
-2.6
1.28
15/01/2010
0
0.3
-1.6
1.29
16/01/2010
0.1
-0.7
-3.9
1.31

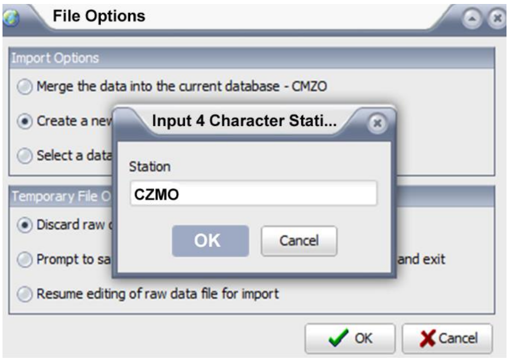

Data Import
File
DATE
RAIN
TMAX
01/01/2010
0.9
4.2
-1
1.13
02/01/2010
0.2
-0.9
-2.2
1.14
Column Property Editor
Column 4
Variable
TMIN
Minimum daily air temperature
Min
Max
Delta
-40
30
20
Units
°C
Degree Celsius (Centrigrade) (Default)
Multiplier
Offset
1.0
0.0
Import this data colum
OK
Cancel
14/01/2010
0
-0.8
-2.6
1.28
15/01/2010
0
0.3
-1.6
1.29
16/01/2010
0.1
-0.7
-3.9
1.31

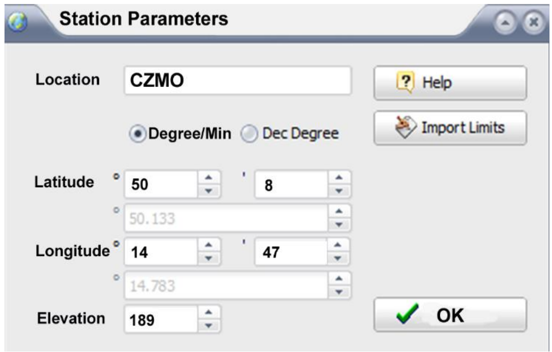


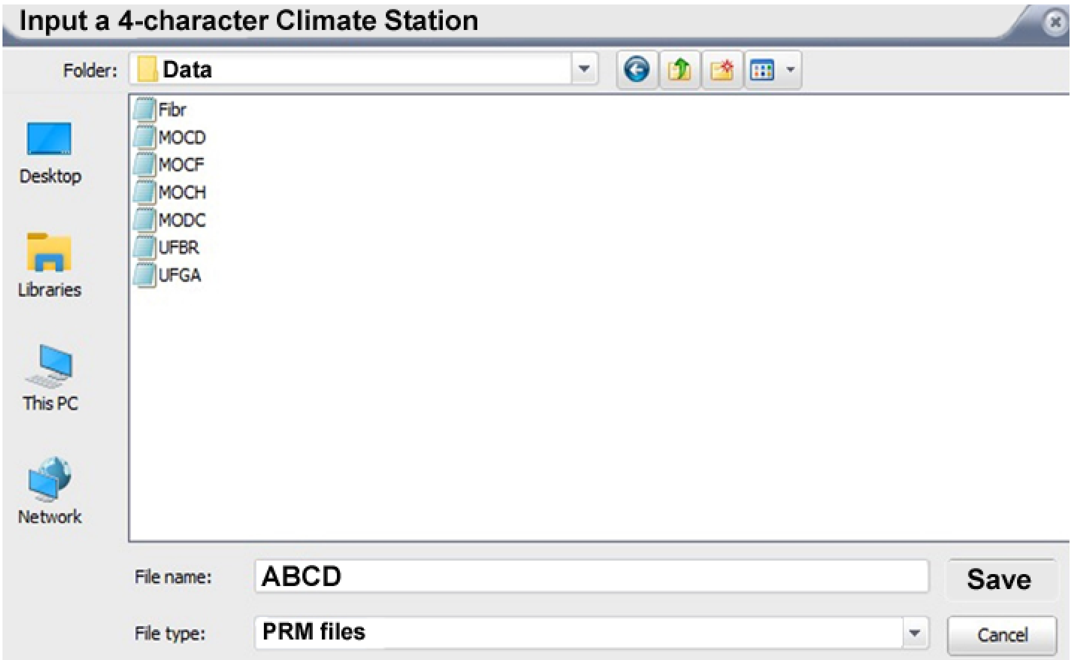
- Import data into WM (weatherman) DSSAT weather files



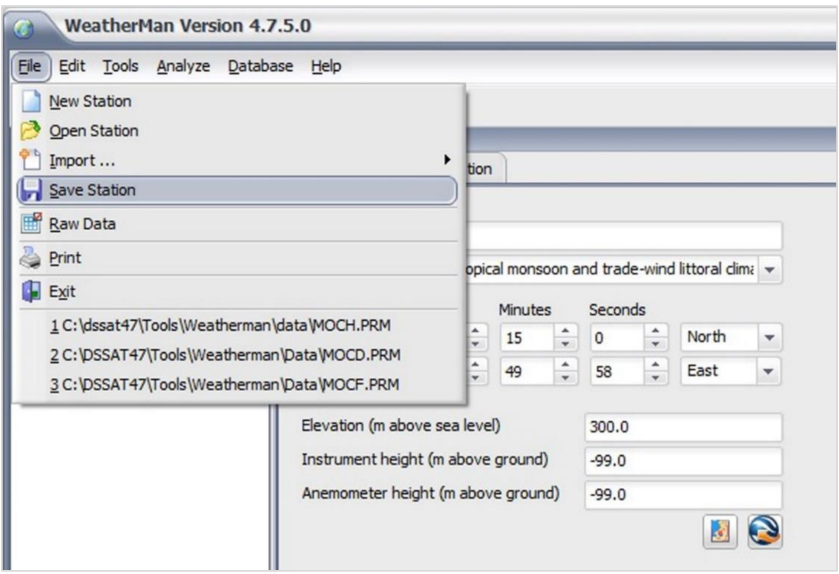
- New weather station naming with basic information



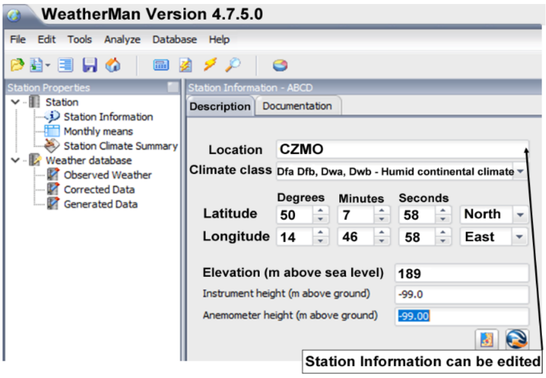




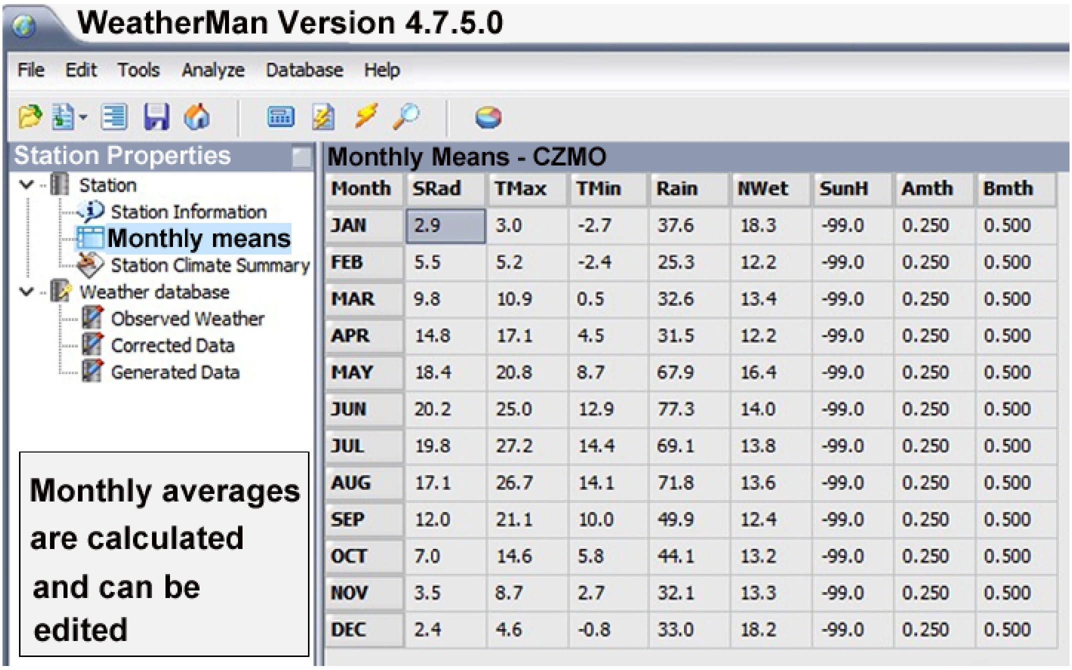
- New weather station with a range of observed years (e.g., here 01/01/2010 – 21/12/2020)



- Check the New weather station



- Monthly summary



Month	SRad	TMax	TMin	Rain	NWet	SunH	Amth	Bmth
JAN	2.9	3.0	-2.7	37.6	18.3	-99.0	0.250	0.500
FEB	5.5	5.2	-2.4	25.3	12.2	-99.0	0.250	0.500
MAR	9.8	10.9	0.5	32.6	13.4	-99.0	0.250	0.500
APR	14.8	17.1	4.5	31.5	12.2	-99.0	0.250	0.500
MAY	18.4	20.8	8.7	67.9	16.4	-99.0	0.250	0.500
JUN	20.2	25.0	12.9	77.3	14.0	-99.0	0.250	0.500
JUL	19.8	27.2	14.4	69.1	13.8	-99.0	0.250	0.500
AUG	17.1	26.7	14.1	71.8	13.6	-99.0	0.250	0.500
SEP	12.0	21.1	10.0	49.9	12.4	-99.0	0.250	0.500
OCT	7.0	14.6	5.8	44.1	13.2	-99.0	0.250	0.500
NOV	3.5	8.7	2.7	32.1	13.3	-99.0	0.250	0.500
DEC	2.4	4.6	-0.8	33.0	18.2	-99.0	0.250	0.500

10.4 Crop Management Component in DSSAT

10.4.1 Crop Data Inputs and Utilities

- Crop Management Dataset
  - minimum dataset
  - soil file structure
  - XBuild (crop management module)

- Collection of crop management dataset
    - crop management data can be collected during the growing period of crops from the crop experimental sites

Fig 10.3 Crop data collection

- Minimum Dataset (depends on Crop types e.g., Winter Oilseed rape)
    - land preparation date (date)
    - previous crop (name)
    - method of planting (dry seed)
    - planting distribution (rows or broadcast)
    - plant population at emergence (plant/m^2)
    - planting date (date)
    - emergence date (date)
    - planting depth (cm)
    - anthesis date (date)
    - plant to plant spacing (cm)
    - row spacing (cm)
    - canopy/plant height (cm)
    - harvest date (date)
    - harvest index at maturity

- harvest yield (kg [dm]/ha)
- leaf area index, maximum (m^2 m^{-2})
- first pod date (date)
- first seed date (date)
- physiological maturity date (date)
- date of harvest maturity stage (date)
- tops weight at anthesis (kg [dm]/ha)
- tops weight at maturity (kg [dm]/ha)
- planting material weight (kg [dm]/ha)
- grain oil at maturity (%)
- grain N at maturity (%)
- number of seeds at maturity (no./unit pod)
- per unit weight at maturity (g [dm]/ha)
- number of pods at maturity (no./m^2)
- number of seeds at maturity (no./m^2)
- fertilizer (if applied- fertilizer materials, date of applications, application methods, amounts (kg/ha))
- irrigation (if applied- date of applications, amount of water (mm), method of application)

- File naming convention
  - AABBNNnn.TMX
    - ✓ AA = Institute Identifier (ID)
    - ✓ BB = Site ID
    - ✓ NN = Year of observation

for example:

- CZMO1401.TMX
  - ✓ CZ = Česká zemědělská univerzita v Praze (Institute ID)
  - ✓ MO = Mochov (Site ID)
  - ✓ 1401 = 2014 (Year of observation with ’01’ experiment number)

10.4.2 DSSAT – Crop Management Module (Xbuild)

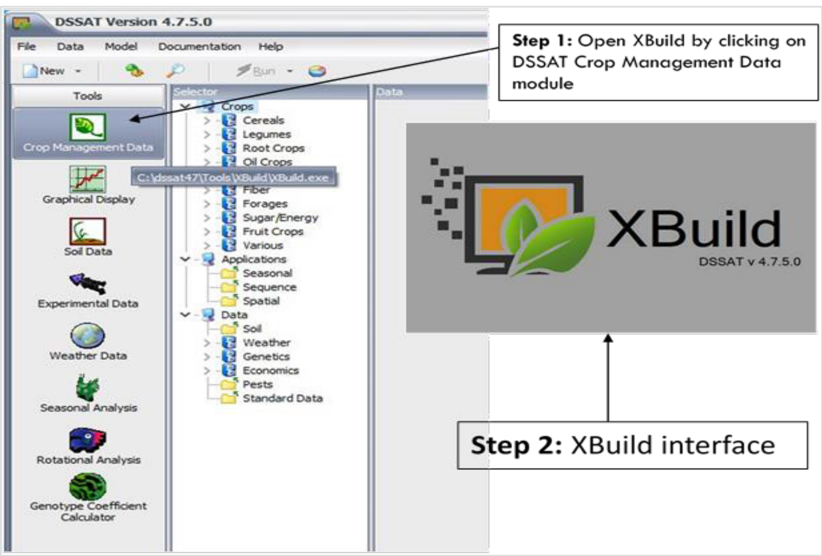
- crop management utility program
- import dataset
- export data in DSSAT format
- fill missing data

- Crop Management File Structure and Header

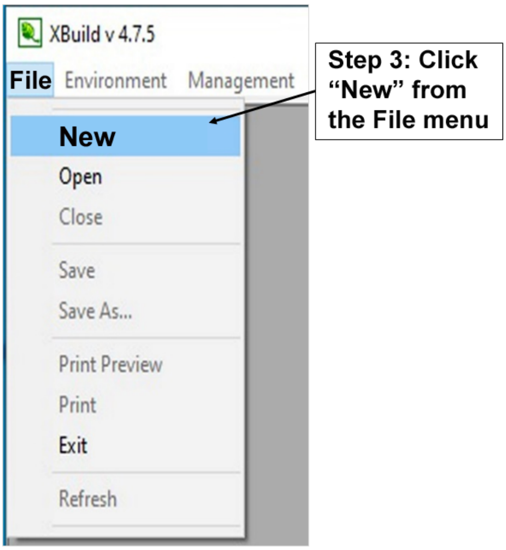
```
*EXP.DETAILS: CZMO1401TM 2014 MOCHOV
*GENERAL
@PEOPLE
@ADDRESS
CZU, Czechea
@SITE
Mochov
@NOTES
*TREATMENTS                -------------FACTOR LEVELS------------
@N R O C TNAME.................... CU FL SA IC MP MI MF MR MC MT ME MH SM
  1 1 0 0 CZMO1401            1  1  1  1  1  0  0  0  0  0  0  1  1
*CULTIVARS
@C CR INGENO CNAME
  1 TM TM0009 Thomas F1
*FIELDS
@L ID_FIELD WSTA....  FLSA  FLOB  FLDT  FLDD  FLDS  FLST SLTX  SLDP  ID_SOIL    FLNAME
 1 CZMO0001 CZMO1401  0     0     DR000  0    0     0000  SA   90    CZCZMO2014 -99
@L ...........XCRD ...........YCRD .....ELEV .............AREA .SLEN .FLWR .SLAS FLHST FHDUR
 1          0          0          0          0       0      0      0     -99   -99
```

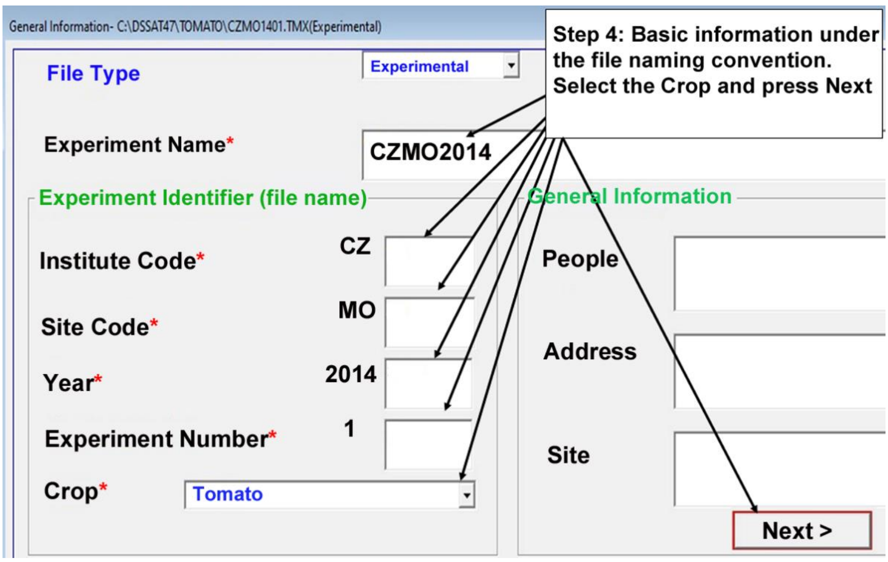
- Data quality
  - missing data (any missing data in DSSAT is called (-99)
  - erroneous data
    - ✓ if the date of an experiment is out of weather year range
    - ✓ if transplanting date is earlier than Planting date
    - ✓ if crop management operations dates are earlier than the Planting date
    - ✓ if maturity date is earlier than Anthesis date etc.

- XBuild detail:

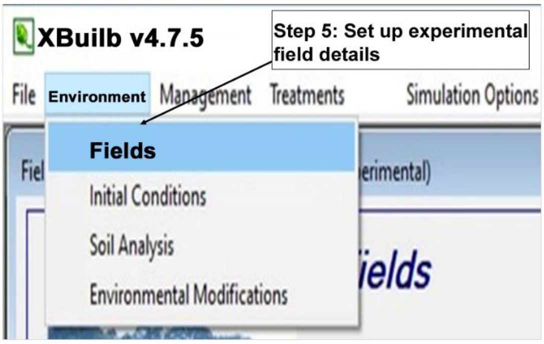


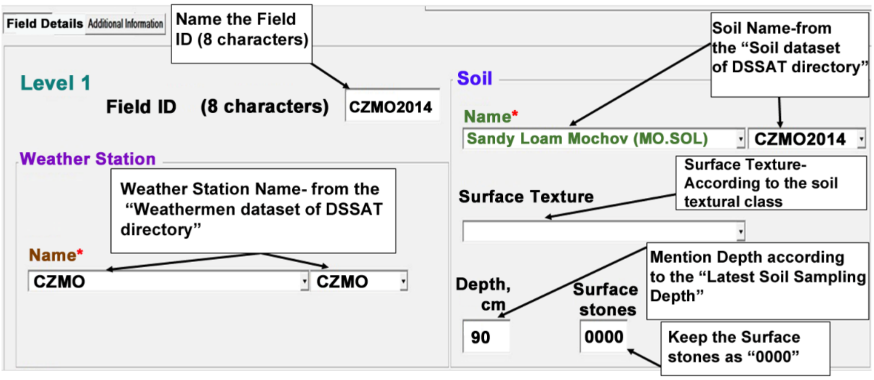
- XBuild- Basic Information

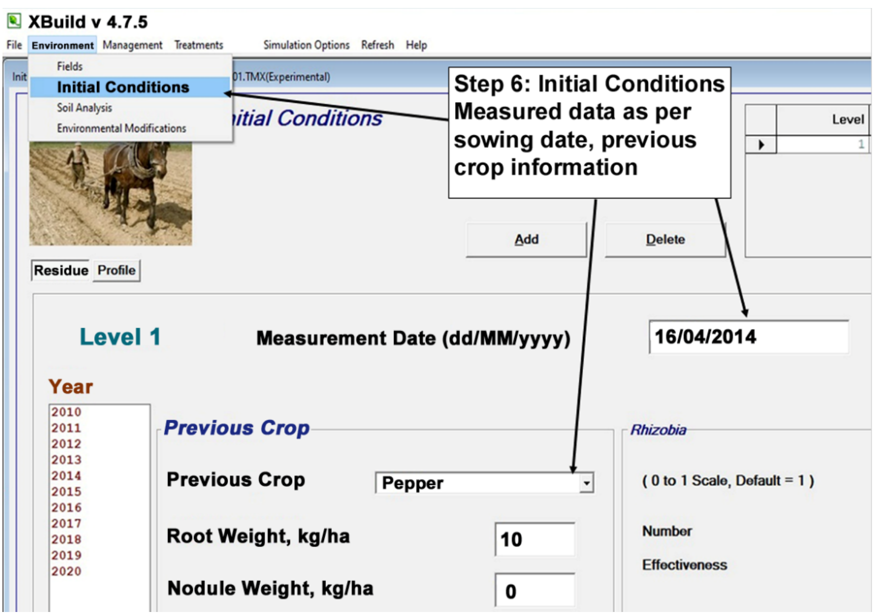


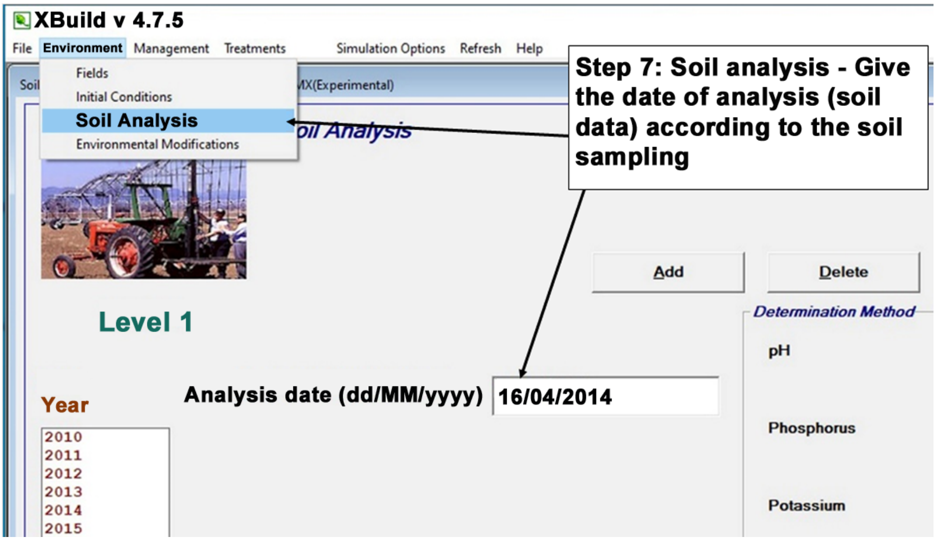


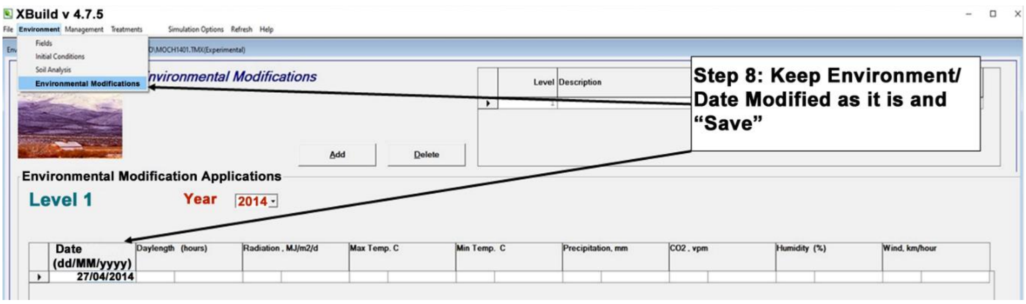
- XBuild- Data Input

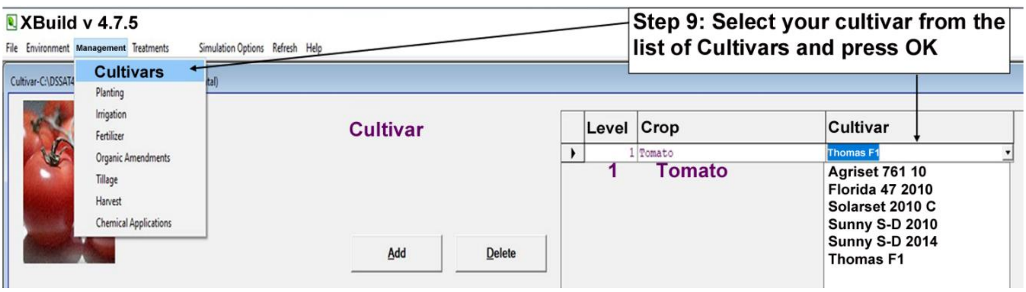


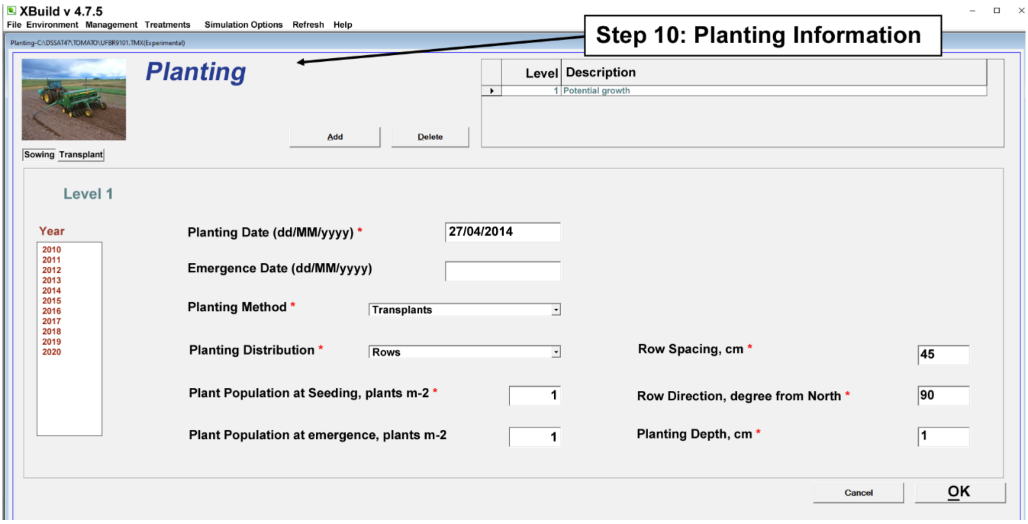


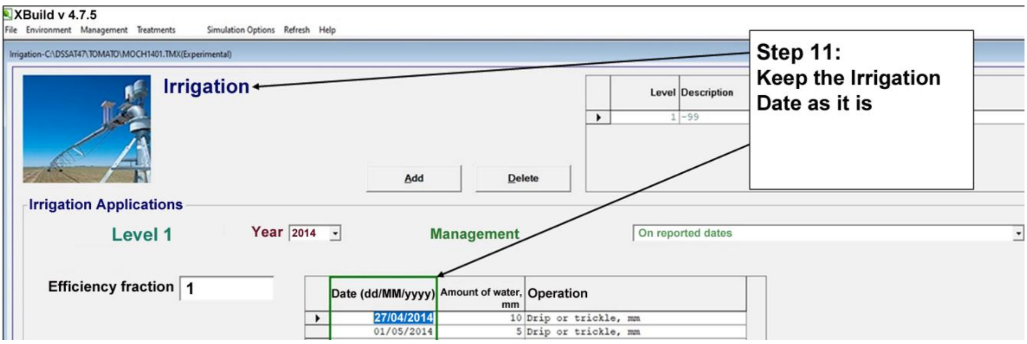


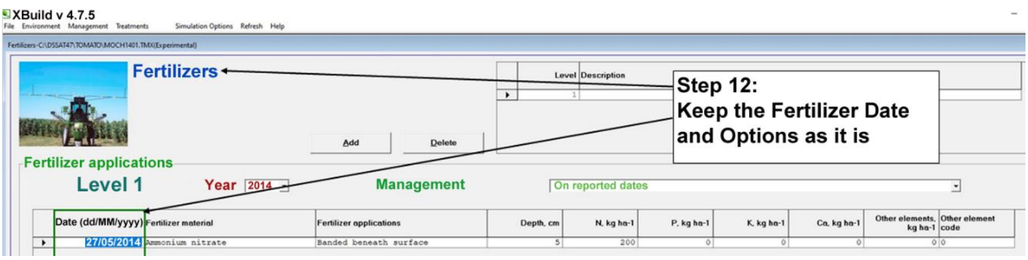

XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Fields
Initial Conditions
Soil Analysis
Environmental Modifications
Step 7: Soil analysis - Give the date of analysis (soil data) according to the soil sampling
Add
Delete
Determination Method
pH
Phosphorus
Potassium
Level 1
Year
Analysis date (dd/MM/yyyy)
16/04/2014
2010
2011
2012
2013
2014
2015

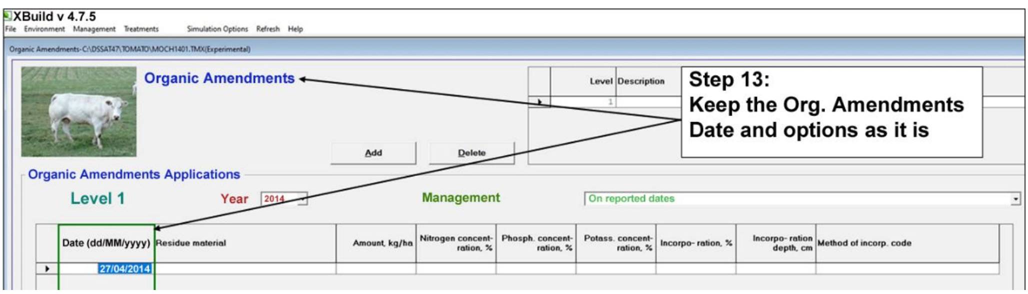

XBuild v 4.7.5
Environmental Modifications
Level
Description
Step 8: Keep Environment/ Date Modified as it is and "Save"
Add
Delete
Environmental Modification Applications
Level 1
Year
2014
Date (dd/MM/yyyy)
27/04/2014
Daylength (hours)
Radiation , MJ/m2/d
Max Temp. C
Min Temp. C
Precipitation, mm
CO2 , vpm
Humidity (%)
Wind, km/hour


XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Step 9: Select your cultivar from the list of Cultivars and press OK
Cultivars
Planting
Irrigation
Fertilizer
Organic Amendments
Tillage
Harvest
Chemical Applications
Cultivar
Add
Delete
Level
Crop
Cultivar
1
Tomato
Thomas F1
Agriset 761 10
Florida 47 2010
Solarset 2010 C
Sunny S-D 2010
Sunny S-D 2014
Thomas F1


XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Step 10: Planting Information
Planting
Level Description
1 Potential growth
Add
Delete
Sowing Transplant
Level 1
Year
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Planting Date (dd/MM/yyyy) * 27/04/2014
Emergence Date (dd/MM/yyyy)
Planting Method * Transplants
Planting Distribution * Rows
Row Spacing, cm * 45
Plant Population at Seeding, plants m-2 * 1
Row Direction, degree from North * 90
Plant Population at emergence, plants m-2 1
Planting Depth, cm * 1
Cancel
OK


XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Irrigation-C:\DSSAT47\TOMATO\MOCH1401.TMX(Experimental)
Irrigation
Step 11: Keep the Irrigation Date as it is
Level Description
1 -99
Add
Delete
Irrigation Applications
Level 1
Year 2014
Management
On reported dates
Efficiency fraction 1
Date (dd/MM/yyyy) Amount of water, mm Operation
27/04/2014 10 Drip or trickle, mm
01/05/2014 5 Drip or trickle, mm


XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Fertilizers-C:\DSSAT47\TOMATO\MOCH1401.TMX(Experimental)
Fertilizers
Level Description
Step 12: Keep the Fertilizer Date and Options as it is
Add
Delete
Fertilizer applications
Level 1
Year 2014
Management
On reported dates
Date (dd/MM/yyyy) Fertilizer material Fertilizer applications Depth, cm N, kg ha-1 P, kg ha-1 K, kg ha-1 Ca, kg ha-1 Other elements, kg ha-1 Other element code
27/05/2014 Ammonium nitrate Banded beneath surface 5 200 0 0 0 0 0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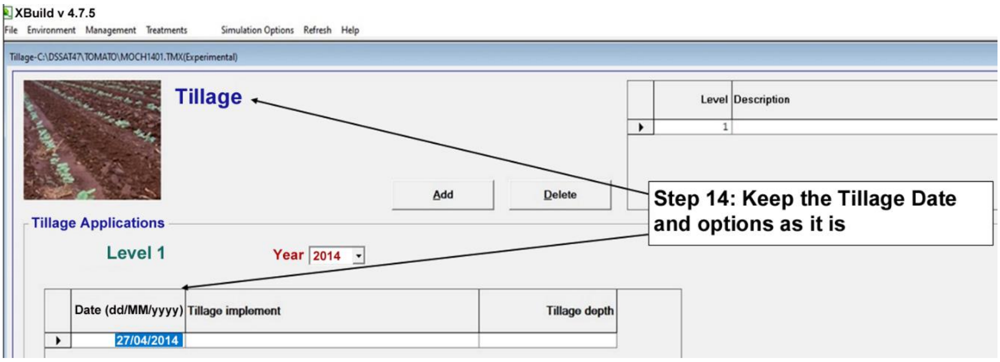
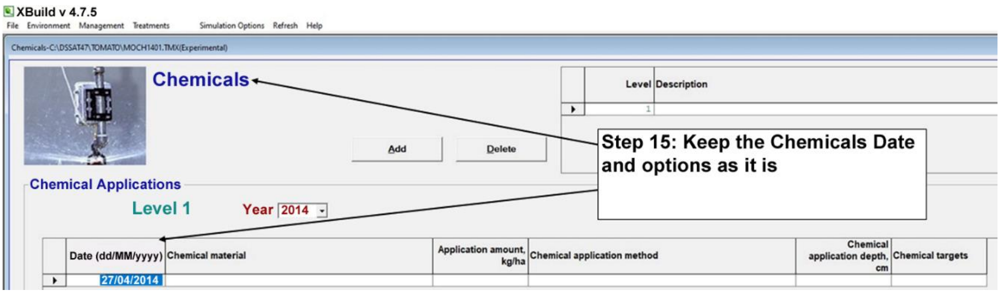
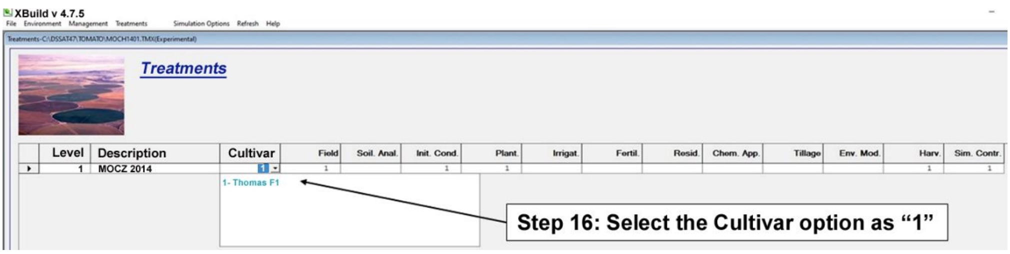
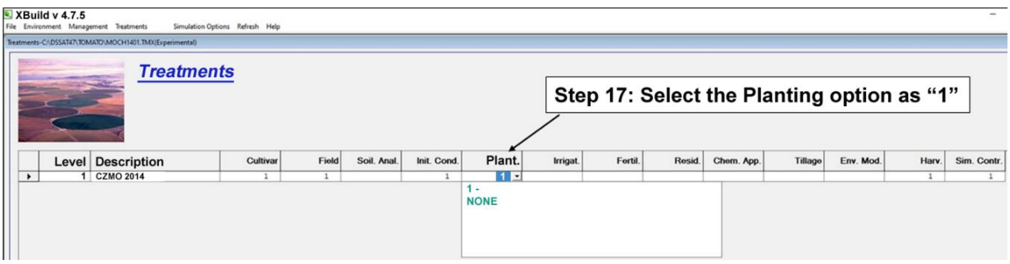
File Environment Management Treatments Simulation Options Refresh Help
Organic Amendments-C:\DSSAT47\TOMATO\MOCH1401.TMX(Experimental)
Organic Amendments
Level Description
Step 13: Keep the Org. Amendments Date and options as it is
Add
Delete
Organic Amendments Applications
Level 1
Year 2014
Management
On reported dates
Date (dd/MM/yyyy) Residue material Amount, kg/ha Nitrogen concent-ration, % Phosph. concent-ration, % Potass. concent-ration, % Incorpo-ration, % Incorpo-ration depth, cm Method of incorp. code
27/04/2014

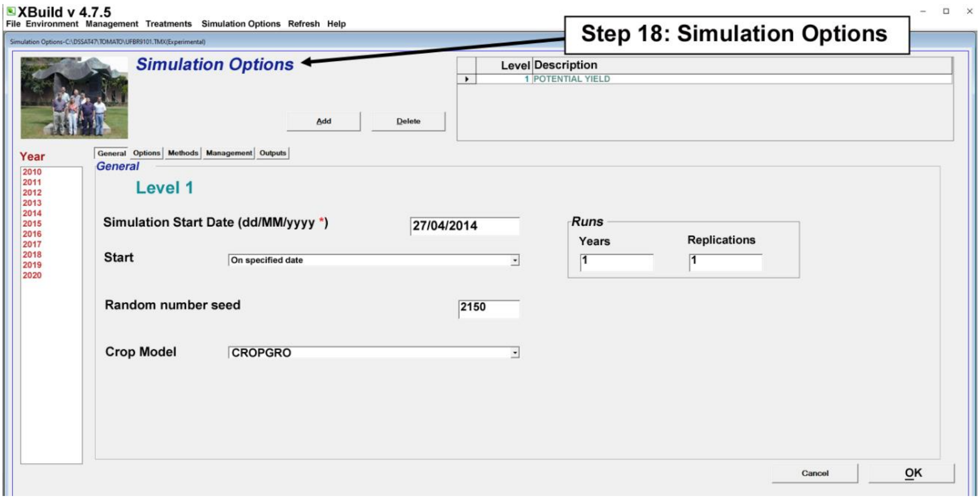

XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Tillage-C:\DSSAT47\TOMATO\MOCH1401.TMX(Experimental)
Tillage
Level Description
1
Add
Delete
Step 14: Keep the Tillage Date and options as it is
Tillage Applications
Level 1
Year 2014
Date (dd/MM/yyyy) Tillage implement Tillage depth
27/04/2014

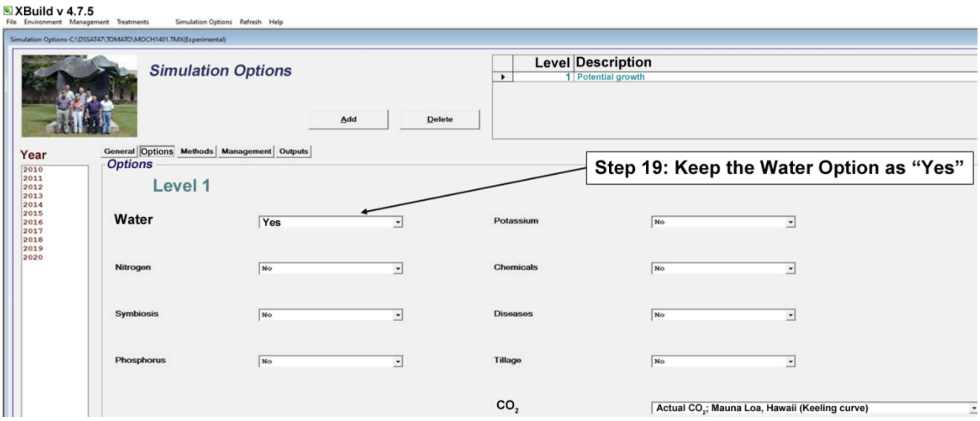

XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Chemicals-C:\DSSAT47\TOMATO\MOCH1401.TMX(Experimental)
Chemicals
Level Description
Add
Delete
Step 15: Keep the Chemicals Date and options as it is
Chemical Applications
Level 1
Year 2014
Date (dd/MM/yyyy) Chemical material Application amount, kg/ha Chemical application method Chemical application depth, cm Chemical targets
27/04/2014

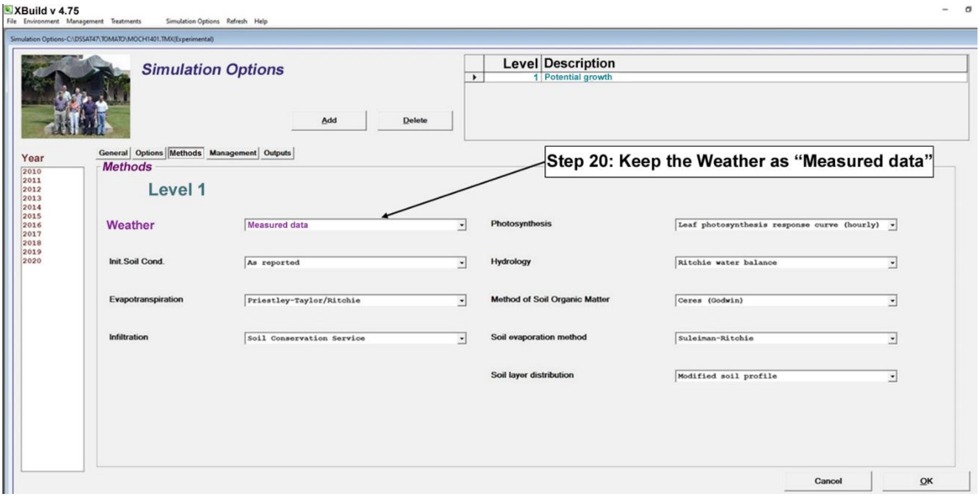

XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Treatments
Level Description Cultivar Field Soil. Anal. Init. Cond. Plant. Irrigat. Fertil. Resid. Chem. App. Tillage Env. Mod. Harv. Sim. Contr.
1 MOCZ 2014 1
1- Thomas F1
Step 16: Select the Cultivar option as "1"

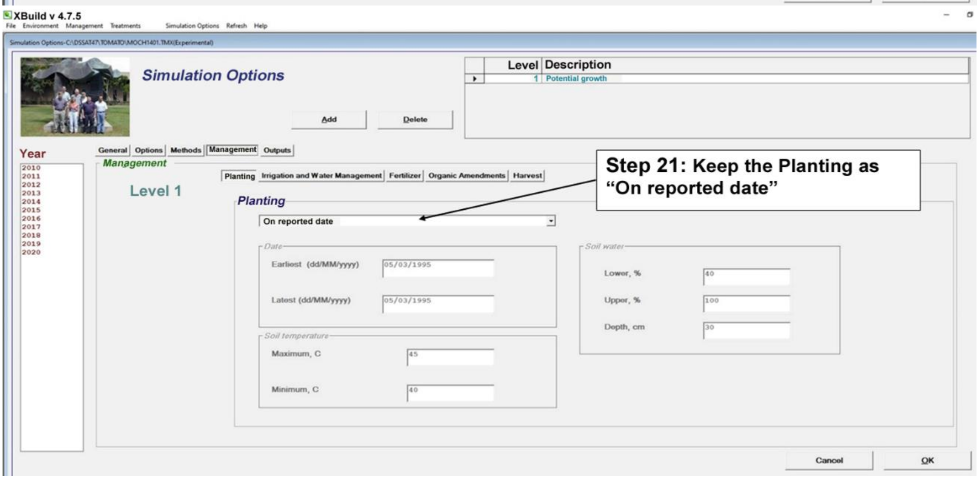

XBuild v 4.7.5
File Environment Management Treatments Simulation Options Refresh Help
Treatments
Step 17: Select the Planting option as "1"
Level Description Cultivar Field Soil. Anal. Init. Cond. Plant. Irrigat. Fertil. Resid. Chem. App. Tillage Env. Mod. Harv. Sim. Contr.
1 CZMO 2014 1
1 -
NONE

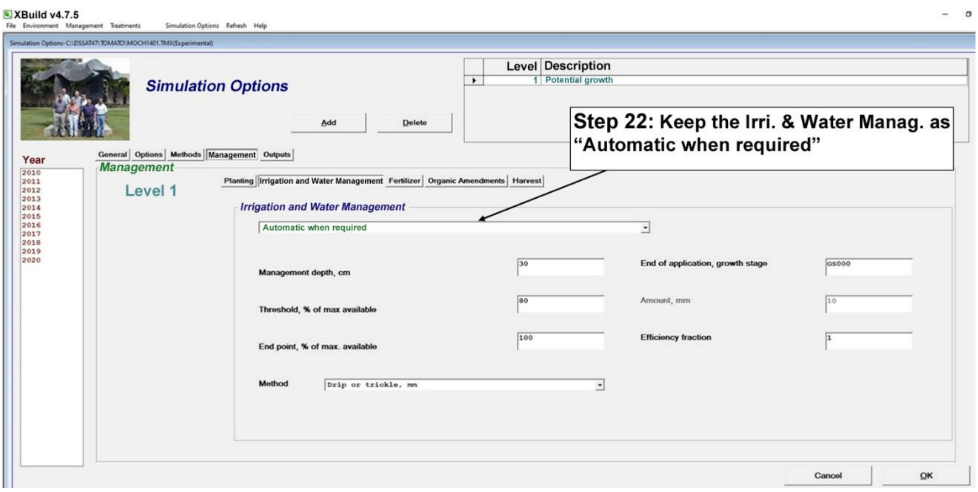
- XBuild- Simulation Options

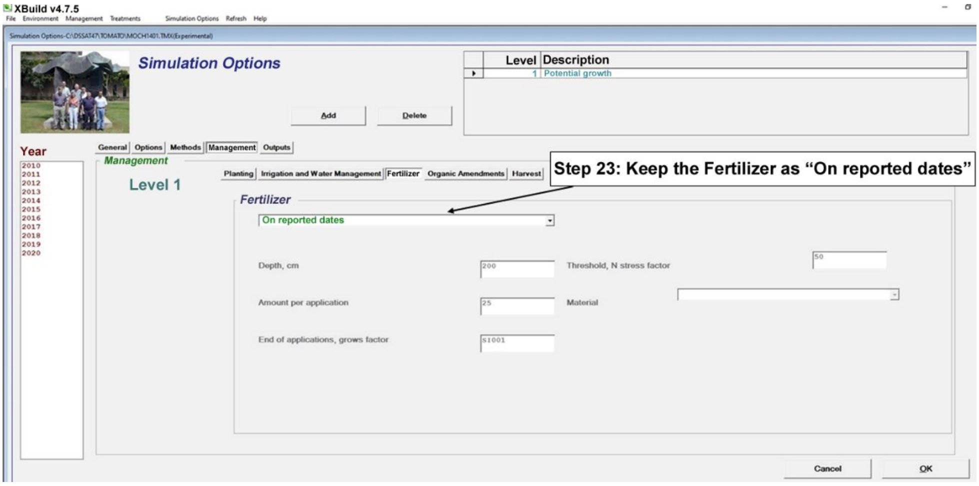


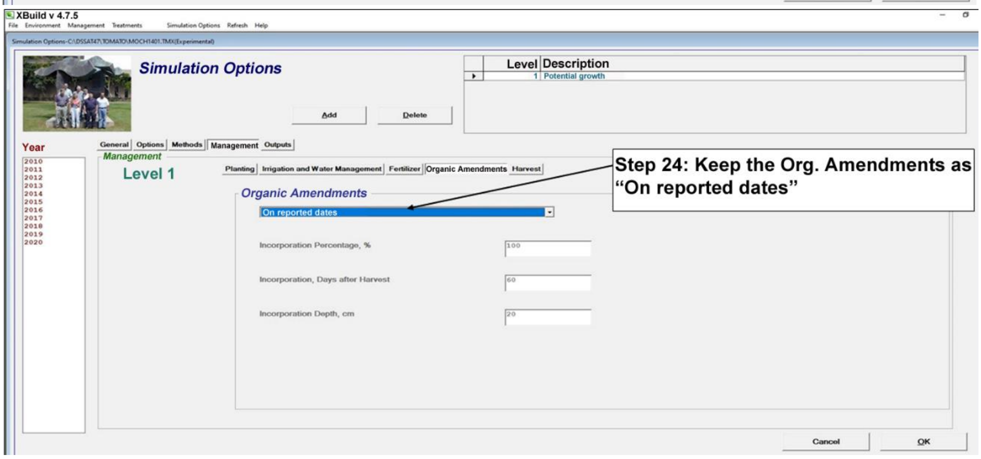


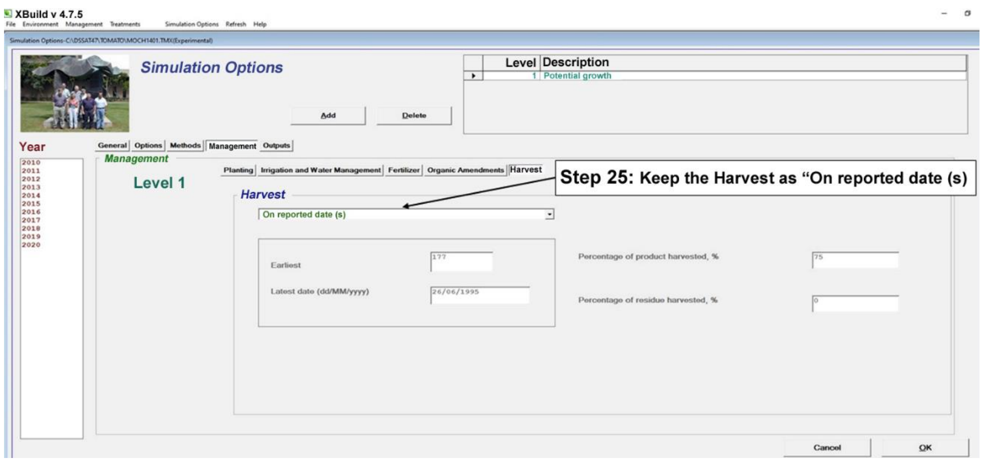

XBuild v 4.75
Simulation Options
Level
Description
1
Potential growth
Add
Delete
Year
General
Options
Methods
Management
Outputs
Methods
Level 1
Step 20: Keep the Weather as "Measured data"
Weather
Measured data
Init.Soil Cond.
As reported
Evapotranspiration
Priestley-Taylor/Ritchie
Infiltration
Soil Conservation Service
Photosynthesis
Leaf photosynthesis response curve (hourly)
Hydrology
Ritchie water balance
Method of Soil Organic Matter
Ceres (Godwin)
Soil evaporation method
Suleiman-Ritchie
Soil layer distribution
Modified soil profile
Cancel
OK


XBuild v 4.7.5
Simulation Options
Level
Description
1
Potential growth
Add
Delete
Year
General
Options
Methods
Management
Outputs
Management
Level 1
Planting
Irrigation and Water Management
Fertilizer
Organic Amendments
Harvest
Step 21: Keep the Planting as "On reported date"
Planting
On reported date
Earliest (dd/MM/yyyy)
05/03/1995
Latest (dd/MM/yyyy)
05/03/1995
Maximum, C
45
Minimum, C
40
Lower, %
40
Upper, %
100
Depth, cm
30
Cancel
OK

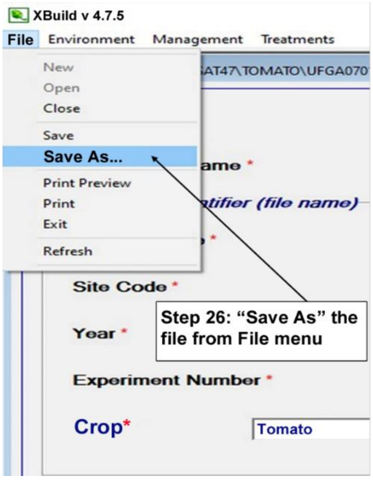

XBuild v4.7.5
Simulation Options
Level
Description
1
Potential growth
Add
Delete
Step 22: Keep the Irri. & Water Manag. as "Automatic when required"
Year
General
Options
Methods
Management
Outputs
Management
Level 1
Planting
Irrigation and Water Management
Fertilizer
Organic Amendments
Harvest
Irrigation and Water Management
Automatic when required
Management depth, cm
30
Threshold, % of max available
80
End point, % of max. available
100
Method
Drip or trickle, mm
End of application, growth stage
GS000
Amount, mm
10
Efficiency fraction
1
Cancel
OK

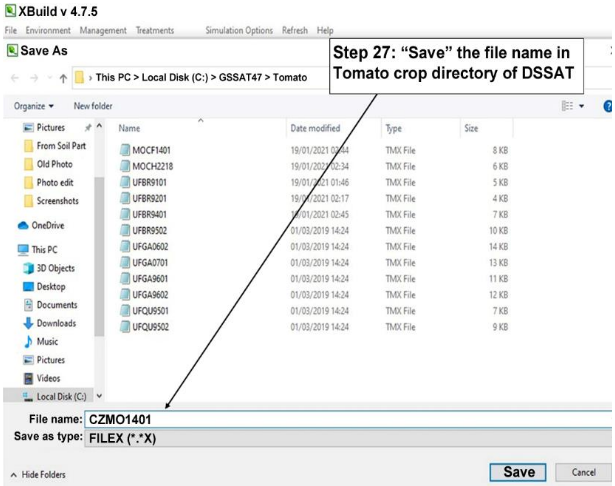

XBuild v4.7.5
Simulation Options
Level
Description
1
Potential growth
Add
Delete
Year
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
General
Options
Methods
Management
Outputs
Management
Level 1
Planting
Irrigation and Water Management
Fertilizer
Organic Amendments
Harvest
Step 23: Keep the Fertilizer as "On reported dates"
Fertilizer
On reported dates
Depth, cm
200
Threshold, N stress factor
50
Amount per application
25
Material
End of applications, grows factor
S1001
Cancel
OK

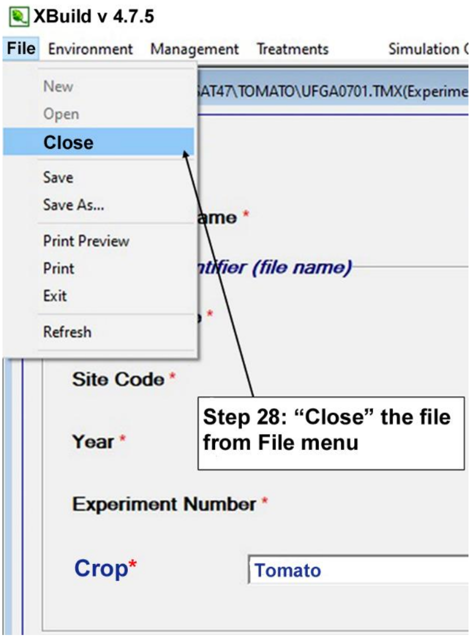

XBuild v 4.7.5
Simulation Options
Level
Description
1
Potential growth
Add
Delete
Year
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
General
Options
Methods
Management
Outputs
Management
Level 1
Planting
Irrigation and Water Management
Fertilizer
Organic Amendments
Harvest
Step 24: Keep the Org. Amendments as "On reported dates"
Organic Amendments
On reported dates
Incorporation Percentage, %
100
Incorporation, Days after Harvest
60
Incorporation Depth, cm
20
Cancel
OK


XBuild v 4.7.5
Simulation Options
Level
Description
1
Potential growth
Add
Delete
Year
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
General
Options
Methods
Management
Outputs
Management
Level 1
Planting
Irrigation and Water Management
Fertilizer
Organic Amendments
Harvest
Step 25: Keep the Harvest as "On reported date (s)
Harvest
On reported date (s)
Earliest
177
Latest date (dd/MM/yyyy)
26/06/1995
Percentage of product harvested, %
75
Percentage of residue harvested, %
0
Cancel
OK

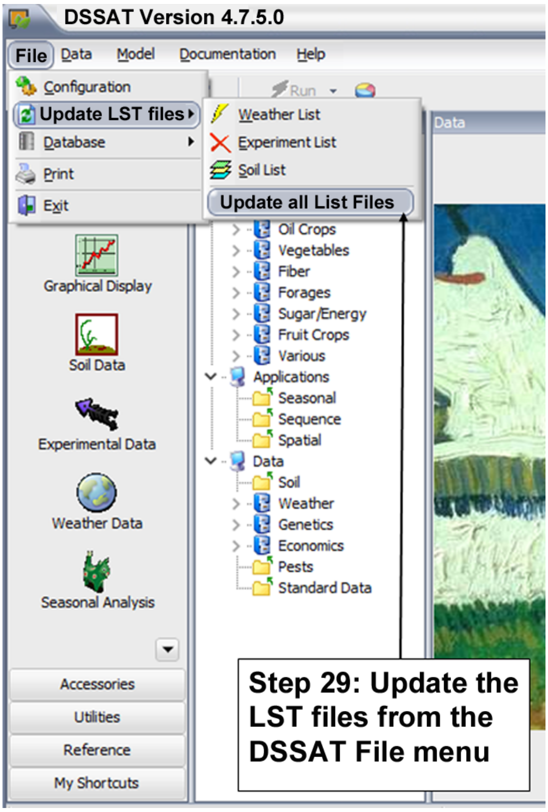
- XBuild- Save profile and close the module







- Update files from the file menu of DSSAT to incorporate the new crop profile



Ch10 Sources:

- Potopová, V. (2021). Study materials published on Moodle – teaching system for teaching support at the Czech University of Life Sciences in Prague. Available from https://moodle.czu.cz/. Lecture 10: Overview of the Decision Support System for Agrotechnology Transfer Crop Simulation Model. Application of DSSAT Crop Simulation Model.

Video Microsoft Stream

Annexure:

Acronyms – Soil Module (SBuild)

@CDE DESCRIPTION

C	Clay
CACO3	CaCO3 content, g kg^{-1}
CL	Clay loam
L	Loam
LAT	Latitude, degrees (decimals; +ve north)
LONG	Longitude, degrees (decimals; +ve east)
LS	Loamy sand
S	Sand
SABD	Bulk density, moist, g cm^{-3}
SABL	Depth, base of layer, cm
SADAT	Analysis date, year + days from Jan. 1
SAHB	pH in buffer
SAHW	pH in water
SAKE	Potassium, exchangeable, cmol kg^{-1}
SALB	Albedo, fraction
SANI	Total nitrogen, %
SAOC	Organic carbon, %
SAPX	Phosphorus, extractable, mg kg^{-1}

SBDM	Bulk density, moist, g cm-3
SC	Silty clay
SCEC	Cation exchange capacity, cmol kg^{-1}
SCL	Silty clay loam
SCOM	Colour, moist, Munsell hue
SCSFAM	Family, SCS system
SDUL	Upper limit, drained, (Field Capacity) cm^3 cm^{-3}
SH20	Water, cm^3 cm^{-3}
SI	Silt
SIC	Silty clay
SICL	Silty clay loam
SIL	Silty loam
SITE	Site name
SL	Sandy loam
SLAL	Aluminium
SLB	Depth, base of layer, cm
SLBS	Base saturation, cmol kg^{-1}
SLCA	Calcium, exchangeable, cmol kg^{-1}
SLCF	Coarse fraction (>2 mm), %
SLCL	Clay (<0.002 mm), %
SLDP	Soil depth, cm
SLDR	Drainage rate, fraction day^{-1}
SLEC	Electric conductivity, milliSiemens per meter (mS/m)
SLFE	Iron
SLHB	pH in buffer
SLHW	pH in water
SLKE	Potassium, exchangeable, cmol kg^{-1}
SLLL	Lower limit, (Lower Limit of plant water extraction) m^3 cm^{-3}
SLMG	Magnesium, cmol kg^{-1}
SLMH	Master horizon
SLMN	Manganese
SLNA	Sodium, cmol kg^{-1}
SLNF	Mineralization factor, 0 to 1 scale
SLNI	Total nitrogen, %
SLOC	Organic carbon, %
SLPA	Phosphorus isotherm A, mmol kg^{-1}
SLPB	Phosphorus iostherm B, mmol l^{-1}
SLPF	Photosynthesis factor, 0 to 1 scale
SLPO	Phosphorus, organic, mg kg^{-1}
SLPT	Phosphorus, total, mg kg^{-1}
SLPX	Phosphorus, extractable, mg kg^{-1}
SLRF	Root growth factor, soil+plant, 0.0 to 1.0
SLRO	Runoff curve no. (Soil Conservation Service)
SLSI	Silt (0.05 to 0.002 mm), %
SLSU	Sulphur
SLTX	Soil texture
SLU1	Evaporation limit, mm
SMHB	pH in buffer determination method, code
SMKE	Potassium determination method, code
SMPX	Phosphorus determination code
SNH4	Ammonium, KCl, g elemental N Mg^{-1} soil
SNO3	Nitrate, KCl, g elemental N Mg-1 soil
SRGF	Root growth factor, soil only, 0.0 to 1.0
SSAT	Upper limit, saturated, (Water contents at saturation) cm^3 cm^{-3}
SSKS	Sat. hydraulic conductivity, macropore, cm h^{-1}

Acronyms – Weather Module (WeatherMan)

@CDE DESCRIPTION

ALPHA	Rainfall distribution scale parameter, monthly, mm^{-2}
AMTH	Angstrom 'a' coefficient, monthly, unitless
ANGA	Angstrom 'a' coefficient, yearly, unitless
ANGB	Angstrom 'b' coefficient, yearly, unitless
BMTH	Angstrom 'b' coefficient, monthly, unitless
DATE	Date, year + days from Jan. 1
DEWP	Daily dewpoint temperature, °C
DURN	Duration of summarization period for climate files, Yr.
ELEV	Elevation, m
EVAP	Daily pan evaporation (mm d^{-1})
GSDU	Growing season duration, Day
GSST	Growing season start day, Doy
INSI	Institute and site code
LAT	Latitude, degrees (decimals)
LONG	Longitude, degrees (decimals)
MTH	Month, #
NAMN	Temperature minimum, all days, monthly average, °C
NASD	Temperature minimum, all days, monthly standard deviation, °C
PAR	Daily photosynthetic radiation, moles m^{-2} day^{-1}
PDW	Probability of a dry-wet sequence
RAIN	Daily rainfall (incl.snow), mm day^{-1}
RAIY	Rainfall, yearly total, mm
REFHT	Reference height for weather measurements, m
RNUM	Rainy days, # $month^{-1}$
RTOT	Rainfall total, mm $month^{-1}$
SAMN	Solar radiation, all days, monthly average, MJ m^{-2} d^{-1}
SDMN	Solar radiation,dry days, monthly average, MJ m^{-2} d^{-1}
SDSD	Solar radiation, dry days, monthly standard deviation, MJ m^{-2} d^{-1}
SHMN	Daily sunshine duration, monthly average, percent
SOURCE	Source of daily weather data, text
SRAD	Daily solar radiation, MJ m^{-2} day^{-1}
SRAY	Solar radiation, yearly average, MJ m^{-2} day^{-1}
START	Start of summary period for climate (CLI) files, Year
SUNH	Daily sunshine duration, percent
SWMN	Solar radiation,wet days, monthly average, MJ m^{-2} d^{-1}
SWSD	Solar radiation, wet days, monthly standard deviation, MJ m^{-2} d^{-1}
TAMP	Temperature amplitude, monthly averages, °C

TAV Temperature average for whole year, °C
TDRY Daily dry-bulb temperature, °C
TMAX Daily temperature maximum, °C
TMIN Daily temperature minimum, °C
TMNY Temperature minimum, yearly average, °C
TMXY Temperature maximum, yearly average, °C
TWET Daily wet-bulb temperature, °C
WIND Daily wind speed (km d^{-1})
WNDHT Reference height for windspeed measurements, m
XAMN Temperature maximum, all days, monthly average, °C
XDMN Temperature maximum, dry days, monthly average, °C
XDSD Temperature maximum, dry days, standard deviation, °C
XWMN Temperature maximum, wet days, monthly average, °C
XWSD Temperature maximum, wet days, standard deviation

Acronyms- Crop Management Module (XBuild)

@CDE DESCRIPTION
ADDRESS Contact address of principal scientist
C Crop component number (default = 1)
CDATE Application date, year + day or days from planting
CHAMT Chemical application amount, kg ha^{-1}
CHCOD Chemical material, code
CHDEP Chemical application depth, cm
CHME Chemical application method, code
CHNOTES Chemical notes (Targets, chemical name, etc.)
CNAME Cultivar name
CNOTES Cultivar details (Type, pedigree, etc.)
CR Crop code
CU Cultivar level
ECO2 CO_2 adjustment, A, S, M, R + vpm
EDATE Emergence date, earliest treatment
EDAY Daylength adjustment, A, S, M, R+h (Add; Subtract; Multiply; Replace)
EDEW Humidity adjustment, A, S, M, R+˚C (Add; Subtract; Multiply; Replace)
EMAX Temp (max) adjustment, A, S, M, R+˚C (Add; Subtract; Multiply; Replace)
EMIN Temp (min) adjustment, A, S, M, R+˚C (Add; Subtract; Multiply; Replace)
ERAD Radiation adjustment, A, S, M, R+MJ $m^{-2}day^{-1}$ (Add; Subtract; Multiply; Replace)
ERAIN Precipitation adjustment, A, S, M, R+mm (Add; Subtract; Multiply; Replace)
EWIND Wind adjustment, A, S, M, R+km day^{-1} (Add; Subtract; Multiply; Replace)
FACD Fertilizer application/placement, code
FAMC Ca in applied fertilizer, kg ha^{-1}
FAMK K in applied fertilizer, kg ha^{-1}
FAMN N in applied fertilizer, kg ha^{-1}
FAMO Other elements in applied fertilizer, kg ha^{-1}
FAMP P in applied fertilizer, kg ha^{-1}
FDATE Fertilization date, year + day or days from planting
FDEP Fertilizer incorporation/application depth, cm
FL Field level
FLDD Drain depth, cm
FLDS Drain spacing, m
FLDT Drainage type, code
FLOB Obstruction to sun, degrees
FLSA Slope and aspect, degrees from horizontal plus direction (W, NW, etc.)
FLST Surface stones (Abundance, % + Size, S, M, L)
FMCD Fertilizer material, code
FOCD Other element code, i.e., MG
HAREA Harvest area, m^{-2}
HARM Harvest method
HCOM Harvest component, code
HDATE Harvest date, year + day or days from planting
HL Harvest level
HLEN Harvest row length, m
HPC Harvest percentage, %
HRNO Harvest row number
HSIZ Harvest size group, code
HSTG Harvest stage
IAME Method for automatic applications, code
IAMT Amount per automatic irrigation if fixed, mm
IC Initial conditions level
ICBL Depth, base of layer, cm
ICDAT Initial conditions measurement date, year + days
ICND Nodule weight from previous crop, kg ha^{-1}
ICRE Rhizobia effectiveness, 0 to 1 scale
ICRN Rhizobia number, 0 to 1 scale
ICRT Root weight from previous crop, kg ha^{-1}
IDATE Irrigation date, year + day or days from planting
IDEP Management depth for automatic application, cm
ID_FIELD Field ID (Institute + Site + Field)
ID_SOIL Soil ID (Institute + Site + Year + Soil)
IEFF Irrigation application efficiency, fraction
IEPT End point for automatic appl., % of max. available
INGENO Cultivar identifier
IOFF End of automatic applications, growth stage
IROP Irrigation operation, code
IRVAL Irrigation amount, depth of water/water table, etc., mm
ITHR Threshold for automatic appl., % of max. available
MC Chemical applications level
ME Environment modifications level
MF Fertilizer applications level
MH Harvest level
MI Irrigation level
MP Planting level
MR Residue level
MT Tillage level

NOTES	**Notes**
O	Rotation component - option (default = 1)
ODATE	Environmental modification date, year + day or days from planting
PAGE	Transplant age, days
PAREA	Gross plot area per rep, m^{-2}
PCR	Previous crop code
PDATE	Planting date, year + days from Jan. 1
PENV	Transplant environment, ˚C
PEOPLE	Names of scientists
PLAY	Plot layout
PLDP	Planting depth, cm
PLDR	Plots relative to drains, degrees
PLDS	Planting distribution, row R, broadcast B, hill H
PLEN	Plot length, m
PLME	Planting method, code
PLOR	Plot orientation, degrees from N
PLPH	Plants per hill (if appropriate)
PLRD	Row direction, degrees from N
PLRS	Row spacing, cm
PLSP	Plot spacing, cm
PLWT	Planting material dry weight, kg ha^{-1}
PPOE	Plant population at emergence, m^{-2}
PPOP	Plant population at seeding, m^{-2}
PRNO	Rows per plot
R	Rotation component - number (default = 1)
RACD	Residue application/placement, code
RAMT	Residue amount, kg ha^{-1}
RCOD	Residue material, code
RDATE	Incorporation date, year + days
RDEP	Residue incorporation depth, cm
RDMC	Residue dry matter content, %
RESK	Residue potassium concentration, %
RESN	Residue nitrogen concentration, %
RESP	Residue phosphorus concentration, %
RINP	Residue incorporation percentage, %
SA	Soil analysis level
SABD	Bulk density, moist, g cm^{-3}
SABL	Depth, base of layer, cm
SADAT	Analysis date, year + days from Jan. 1
SAHB	pH in buffer
SAHW	pH in water
SAKE	Potassium, exchangeable, cmol kg^{-1}
SANI	Total nitrogen, %
SAOC	Organic carbon, %
SAPX	Phosphorus, extractable, mg kg^{-1}
SH2O	Water, cm^3 cm^{-3}
SITE(S)	Name and location of experimental site(s)
SLDP	Soil depth, cm
SLTX	Soil texture
SM	Simulation control level
SMHB	pH in buffer determination method, code
SMKE	Potassium determination method, code
SMPX	Phosphorus determination method, code
SNH4	Ammonium, KCl, g elemental N Mg^{-1} soil
SNO3	Nitrate, KCl, g elemental N Mg^{-1} soil
TDATE	Tillage date, year + day
TDEP	Tillage depth, cm
TDETAIL	Tillage details
TIMPL	Tillage implement, code
TL	Tillage level
TN	Treatment number
TNAME	Treatment name
WSTA	Weather station code (Institute + Site)

***Element Code**

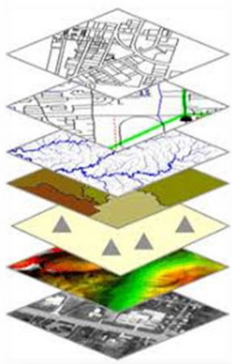
@CDE	DESCRIPTION
B	Boron
CA	Calcium
FE	Iron
MG	Magnesium
N	Nitrogen
P	Phosphorus
P	Potassium
S	Sulphur
ZN	Zinc

***Soil Texture**

C	Clay
CL	Clay loam
L	Loam
LS	Loamy sand
S	Sand
SC	Silty clay
SCL	Silty clay loam
SI	Silt
SIC	Silty clay
SICL	Silty clay loam
SIL	Silty loam
SL	Sandy loam

Chapter 11

Geographic Information Systems – components, tools, and application in climate change modelling



Keywords:

- Geographic Information Systems (GIS)
- geospatial database
- spatial data
- web GIS tools
- desktop GIS tools

Chapter 11: Geographic Information Systems - components, tools, and application in climate change modelling

11.1 Introduction

Climate change can be assessed using GIS techniques and software. Geographic information systems (GIS) are a type of computer programs that allows users to query and analyse spatial information and create maps that show the results of those operations.
Using GIS software, we are able to manage different types of spatial and non-spatial data, as well as integrate those data from different sources, with different formats, structures, projections, etc. using a computer. There are two widely used models for storing data in a GIS: the raster data model and the vector model.

11.2 Components of GIS

- The computer system (hardware and the operating system).
- The GIS software package.
- Data management and analysis procedures (data storage and retrieval, maintenance and updating). Spatial analysis is the most important function of the GIS.

- The people to operate the GIS. They are many categories of GIS users, starting from GIS professionals, map and applications creators, map editors, field workers, insights analysts, map viewers, or even storytellers (ESRI).

11.3 Web-based Geospatial Tools for Assessing Climate Change

IPCC WGI Interactive Atlas is a tool used for spatial and temporal analyses of the observed and projected climate change information, including regional synthesis (Fig. 11.1) (https://interactive-atlas.ipcc.ch/)

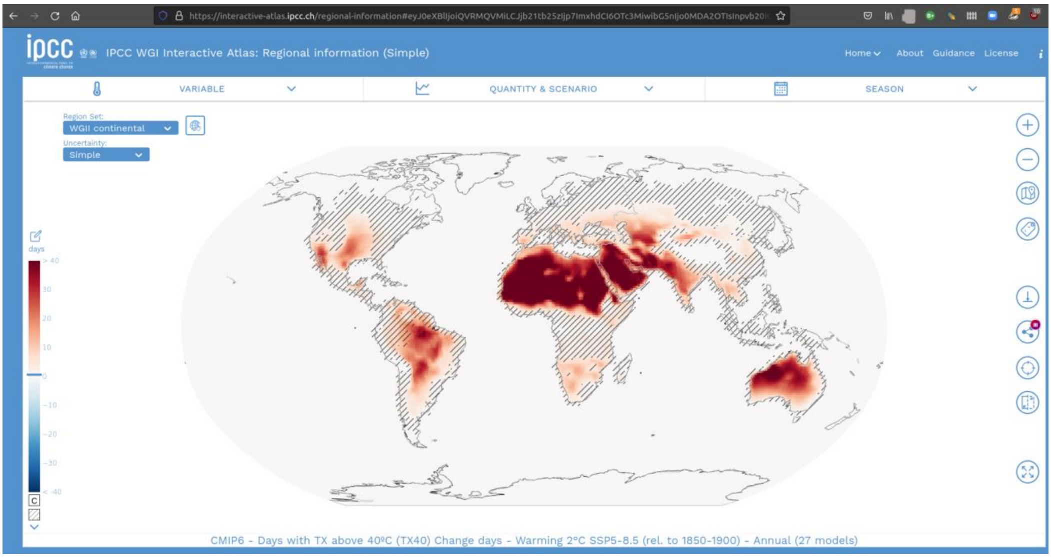


Fig. 11.1 IPCC WGI Interactive Atlas

IPCC AR6 Sea Level Projection Tool - allows users to visualize and download the sea level projection data from the IPCC AR6, both global and regional, from 2020 to 2150 (Fig. 11.2) (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool).

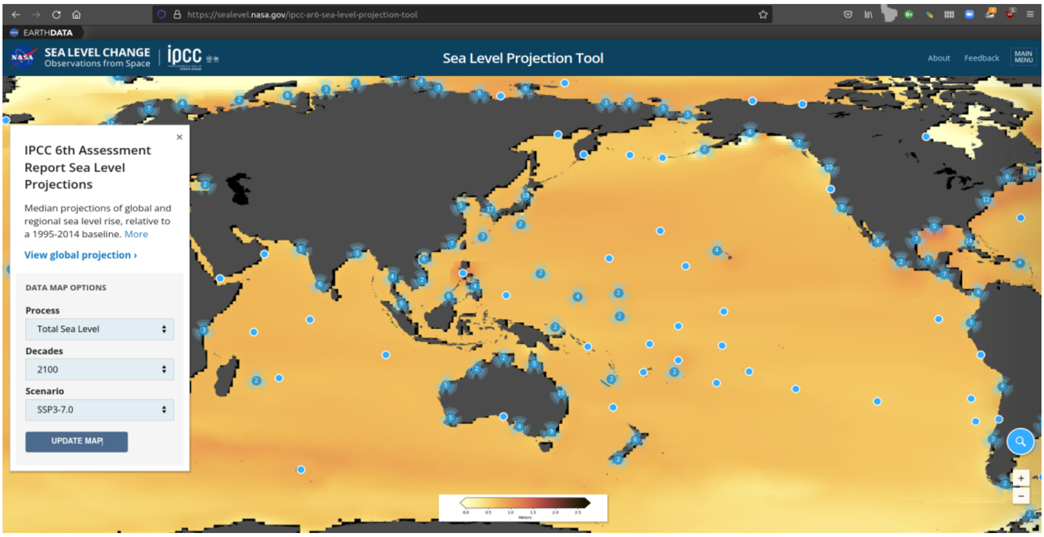


Fig. 11.2 IPCC AR6 Sea Level Projection Tool

11.4 Climate GIS Data Sources

In terms of data sources, at the moment, we can talk about a wide and ever-increasing variety of weather data, which can be used for different purposes and data requirements:

- Google's Dataset Search Engine is a search engine that allows you to find data available online and for free https://datasetsearch.research.google.com/
- The CCAFS-Climate data portal provides high-resolution climate data sets on the impact of climate change and adaptation for a wide range of areas http://www.ccafs-climate.org/
- The CRUTEM4 land temperature data set is a set of data derived from air temperatures near the ground surface that come from weather stations on all continents http://www.cru.uea.ac.uk/cru/data/crutem/ge/
- The European Center for Medium-Range Weather Forecasts (ECMWF) is the operator of one of the largest weather forecast data archives in the world https://www.ecmwf.int/
- European Space Agency Climate Change Initiative (ICC) – was created as a result of the development of satellite data sets over more than 40 years https://climate.esa.int/en/
- ESRI's GIS for Climate Hub has a variety of resources useful for a variety of climate analysis https://climate-arcgis-content.hub.arcgis.com/
- Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE) is a publicly accessible repository of data for research and modelling purposes https://ess-dive.lbl.gov/
- The European Climate Assessment and Dataset (ECAD) contains grid observation data for the territory of Europe, with reference to cloud cover, temperatures, precipitation, humidity, etc. https://www.ecad.eu/
- FAO GeoNetwork consists of 247 sets of climate spatial data, including satellite imagery https://www.fao.org/geospatial/resources/data-portals/geonetwork/en/

- Global Historical Climatology Network monthly (GHCNm) provides monthly climate summaries from thousands of globally distributed weather stations http://www.ncdc.noaa.gov/ghcnm/
- The Global Historical Climatology Network (GHCNd) provides daily climate summaries from thousands of globally distributed weather stations (over 100,000 stations) (80 countries) https://www.ncdc.noaa.gov/ghcnd-data-access.
- Global-PET and Global-Aridity datasets consist of high-resolution raster climate data with global coverage with reference to evapotranspiration and rainfall deficit https://figshare.com/articles/dataset/Global_Aridity_Index_and_Potential_Evapotranspiration_ET0_Climate_Database_v2/7504448/3
- The Global SPEI database contains SPEI drought index data https://spei.csic.es/database.html
- The Global Precipitation Climatology Center (GPCC) provides monthly precipitation data from 1901 to the present, calculated from data from the global network of weather stations http://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html
- NASA Earth Observatory has been providing data on 16 climatic factors (aerosols, temperatures, and carbon) since 1999 https://earthobservatory.nasa.gov/
- NASA GISS datasets consist of Earth observation data (temperatures, aerosols, nebulosity, precipitation, solar radiation, etc.) as well as simulated data http://data.giss.nasa.gov/
- NASA’s Socioeconomic Data and Applications Center (SEDAC) has data on human interactions with the environment (123 data sets) https://sedac.ciesin.columbia.edu/
- NCEI and the World Data Service for Paleoclimatology have the largest archive of climate and paleoclimatological data https://www.ncei.noaa.gov/products/paleoclimatology
- NCAR GIS-based Climate Change Scenario provides free data sets on climate change projections http://gisclimatechange.ucar.edu/
- NOAA's NCEI provides public access to its archive of environmental data on the atmosphere, coastal regions, oceans, etc. http://www.ncdc.noaa.gov/oa/ncdc.html
- UNEP Environmental Data Explorer has over 500 different variables good to explore and use https://ede.grid.unep.ch/
- WorldClim is a global weather and climate database. This data can be used for mapping and spatial modelling https://www.worldclim.org/

11.5 Desktop GIS Tools

11.5.1 Steps for Preparing Maps for Climate Change Analysis and Modelling using GIS

- create a database
- create/Acquire data layers
- decide on your GIS framework conditions (precision and scale)
- process your data
- create a GIS project
- add data to the project
- create points, lines, polygons, image, and grid according to Table 11
- analyse your data
- use your data as inputs for models

- map your modelling results

Table 11.1 Geometries and Data Formats for Weather Data (Matouq et al., 2014)

Shape (Geometry)	Weather data types
Point	Surface observation, rain gauge, river gauge, reports, model grid-point data
Line	Contours, fronts, rivers, roads and road conditions, air parcel trajectories
Polygon	Radar, area forecast, plumes
Image	Satellite images, charts
Grid	Surfaces (all data with continuous distribution: elevation, pressure, temperature, precipitations, soil moisture, soil content etc.)

11.5.2 BASINS Climate Assessment Tool (CAT)

Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) is a software designed U.S. Environmental Protection Agency for environmental analysis. BASINS Climate Assessment Tool (CAT) is one of the BASINS system components, providing a set of capabilities to help investigating the potential effects of climate change on water flow and water quality using modelling. The tool also allows creation and analysis of climate change scenarios (https://www.epa.gov/).

11.5.3 Managing climate modelling data with XyGrib

XyGrib is a Grib file reader and visualizer for meteorological data providing an off-line capability to analyse weather forecasts or hindcasts. XyGrib can display weather data from numerous sources in Grib formats (Fig. 11.3) (https://opengribs.org/).

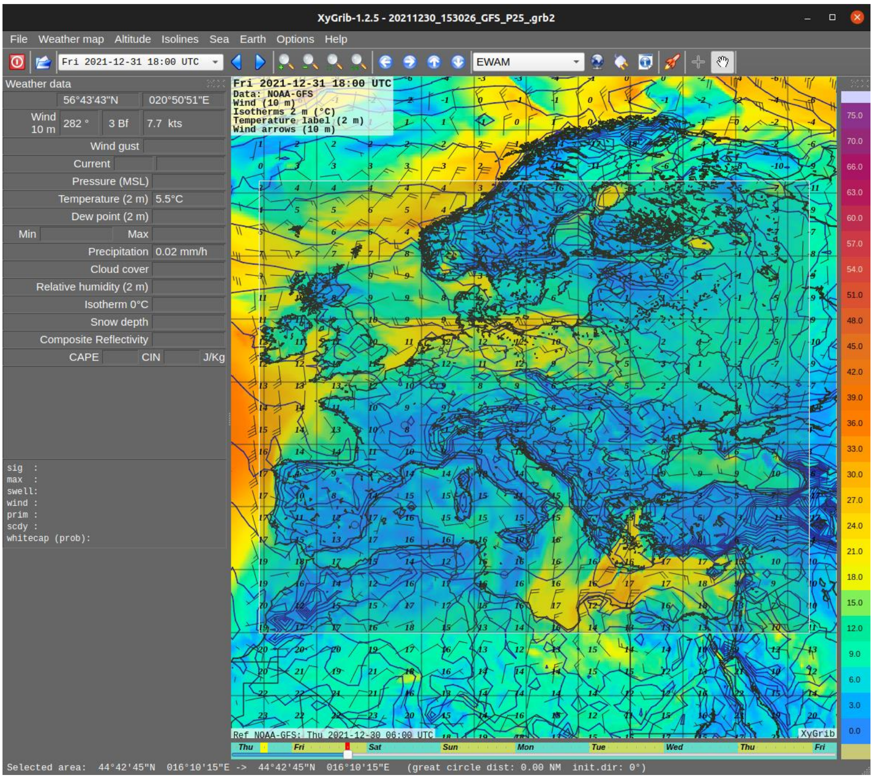


Fig. 11.3 XyGrib GUI with loaded data

11.5.4 Working with climate data in QGIS

QGIS is an open-source Geographic Information System. It is user friendly, offering functions and features common to the majority of GIS. QGIS can be used to solve a variety of tasks, starting from capturing and viewing geospatial data, advanced spatial analysis, and, ending with creating complex maps and reports. QGIS supports a large variety of raster and vector data formats, and its plugin-based architecture allows a rapid addition of new capabilities (https://www.qgis.org/).

Adding GRIB data to QGIS can be done through the generic QGIS Data Source Manager (via MDAL library), or using plugins such as: QGribDownloader (for downloading data) or Crayfish (for adding and manipulating locally stored data, after previously downloaded, for example, using ZyGrib) (Fig. 11.4). For example, the Crayfish plugin allows you to:

- see live traces of the wind
- plot the time series
- generate animations for your data

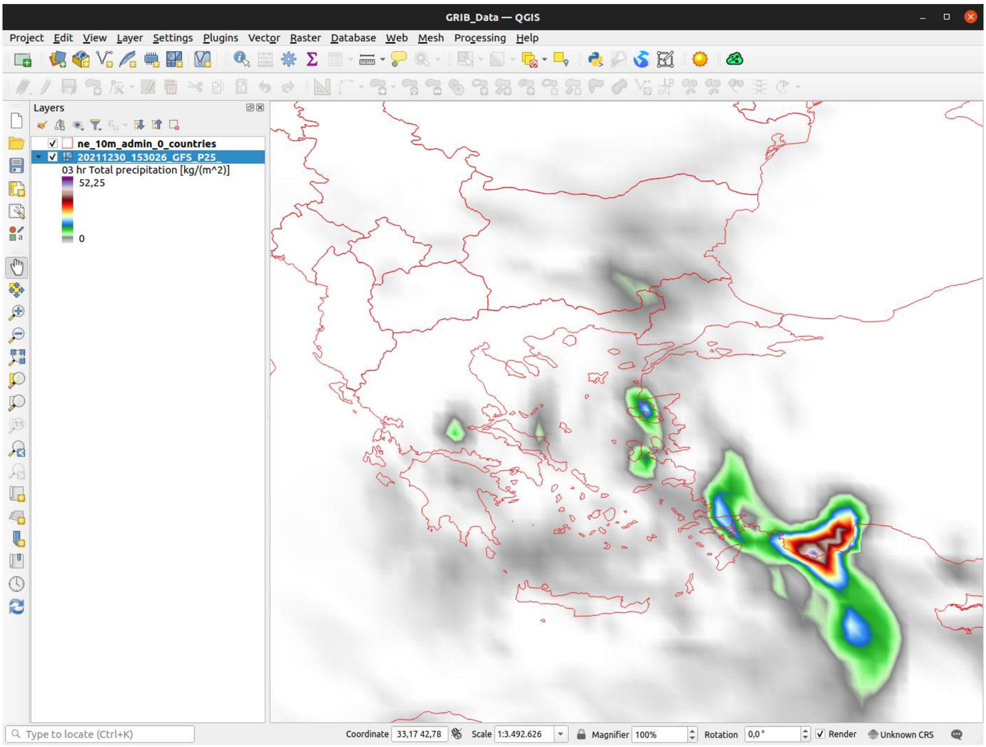


Fig. 11.4 QGIS with forecasting data in GRIB format loaded

11.6 GIS for Climate Change Studies

Researchers are using GIS in a variety of ways for better understand of climate change very complex situation, including:

- locating areas where temperatures or precipitations are unusually higher compared to the global average (Fig. 11.5)
- determining the natural atmospheric processes that affect global warming
- developing models to demonstrate how a warming climate could affect the ecology of different regions
- investigating the relationship between climate change and waters, soil, and vegetation changes
- visualising a variety of factors that have the potential to affect humans, agriculture, industry, or wildlife

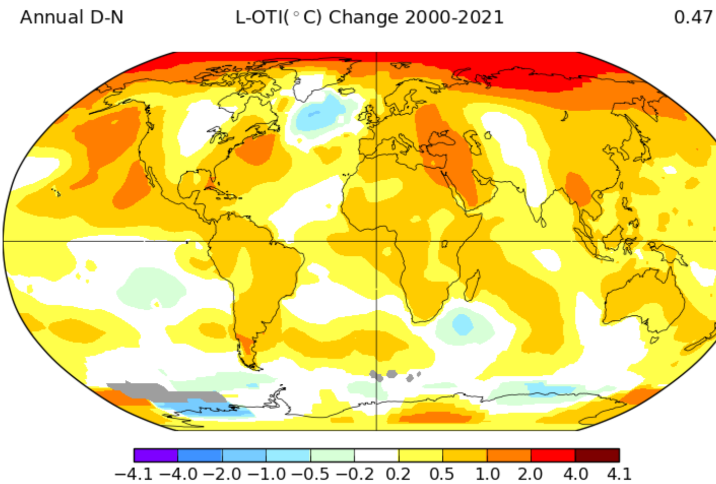


Fig. 11.5 GISS Surface Temperature Analysis (v4) (GISTEMP, 2021)

11.7 GIS Applications in Climate Change Detection and Monitoring

- GIS technology uses data collected from a variety of sources, such as satellite imagery or various sensors, and uses maps to identify environmental issues, establish links between climate change and other hazards, and predict future transformations
- Using geospatial techniques, researchers can gather more information about the connections between climate change and weather patterns and can predict adverse events in advance
- GIS techniques include performing queries, GIS statistical functions, and GIS data can also be displayed as maps, graphs, and charts for visualization and analysis purposes

Overall, the use of Geographic Information Systems covers a variety of climate change related areas, helping to solve a wide range of problems, such as:

- Assessing Impact of Climate Change on Economic Resources – deforestation and reforestation areas identification, assessing and conservation of critical resources, biodiversity changes etc.
- Using GIS for Climate Change-related Issues Mapping – solar and wind potential mapping, carbon content monitoring, ice shelf mapping etc.
- GIS for Climate Change Disaster Response – improve our understanding of how climate change affects communities or infrastructure, the satellite imagery and other remote sensing data can support the authorities to produce hazard maps and identify the areas that are worst affected and need immediate attention
- Using GIS for Climate Change Mitigation and Adaptation - GIS mapping and analysis are effective in geographic planning and environmental changes identification and for further implementing action plans

Ch11 Sources:

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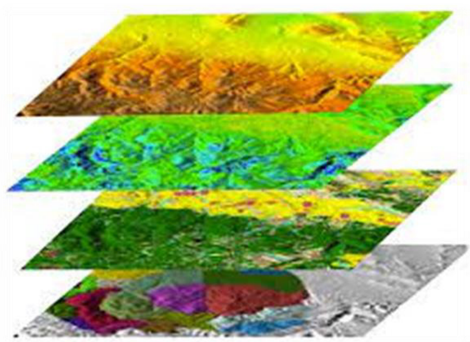
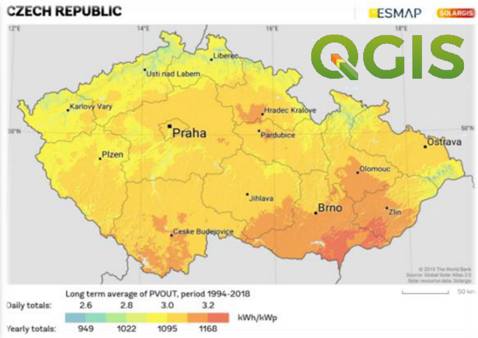
Chapter 12

Using QGIS for climate change modelling



Keywords:

- QGIS
- bioclimatic Indices
- temporal analysis
- spatial analysis



Chapter 12: Using QGIS for climate change modelling

12.1 Using GIS for Climate Change Assessment

- Software used: QGIS 3.22.2
- Open source, freely available (Fig. 12.1)
- Go to this site to find out about QGIS: http://www.qgis.org/
- QGIS User Guide: https://docs.qgis.org/3.22/en/docs/user_manual/
- QGIS Training Manual: https://docs.qgis.org/3.22/en/docs/training_manual/index.html
- Download and install QGIS. https://www.qgis.org/en/site/forusers/download.html

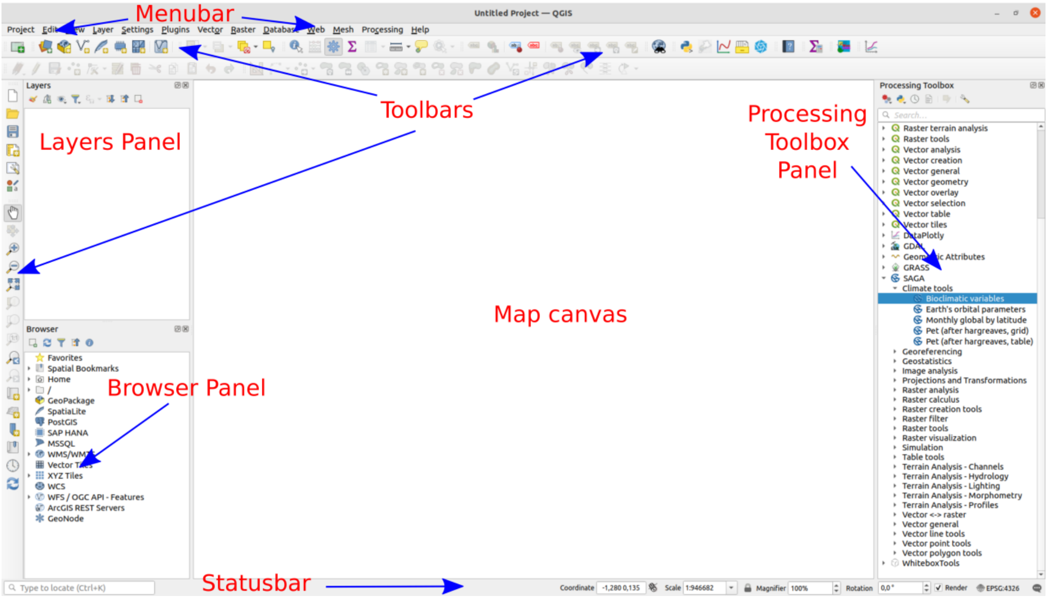


Fig. 12.1 QGIS 3.22.2 GUI

- Activate plugins and processing options. SAGA GIS and GRASS GIS providers, we find very useful.

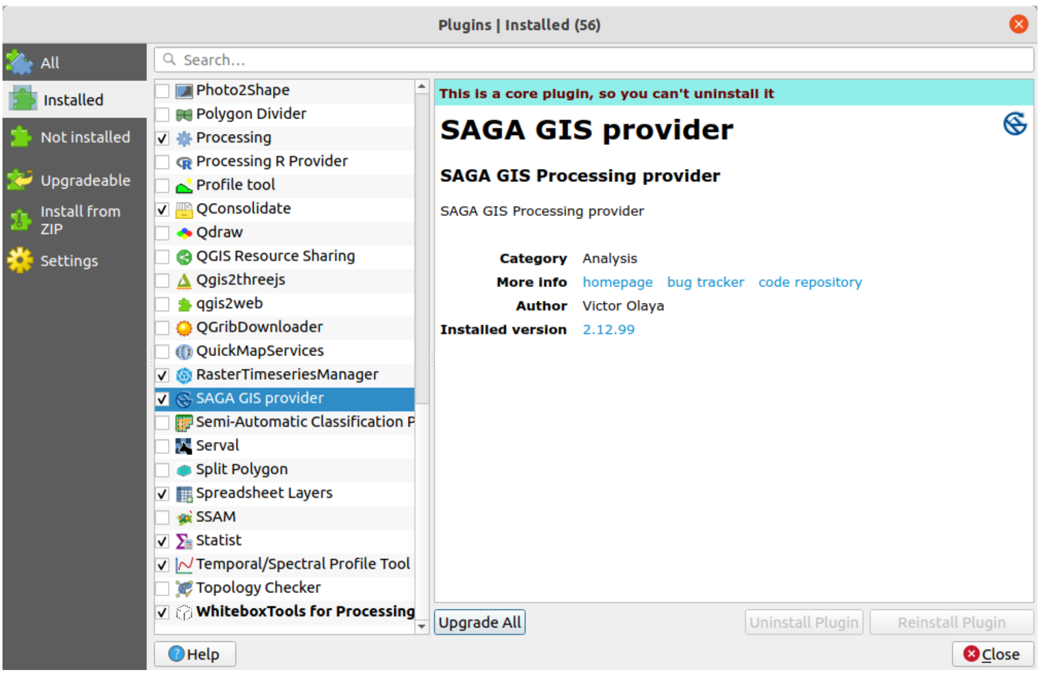


Fig. 12.2 SAGA GIS provider plugin

12.2 Determination of Bioclimatic Variables using QGIS

Bioclimatic variables are derived from the monthly average values of temperatures and precipitation in the sense of obtaining more biologically significant derived variables. They are often used in modelling the distribution of species and related ecological (and agricultural) modelling techniques. Bioclimatic variables represent annual trends, seasonality, and extreme environmental factors (Fick and Hijmans, 2017) (Fig. 12.2).

WorldClim is a high-resolution raster global weather and climate database. This data can be used for mapping and spatial modelling, for use in research and related activities (Fick and Hijmans, 2017). Even though WorldClim offers Bioclimatic Indices for download, we will create these values individually, using the *Bioclimatic Variables* tool from SAGA GIS software (Table 12.1). We will invoke it from within QGIS GUI via the Processing Toolbox and the SAGA GIS provider plugin. This tool calculates biologically relevant variables from monthly climate data (mean, minimum and maximum temperature, and precipitation), as provided by the WorldClim project (Fick and Hijmans, 2017).

Table 12.1 Bioclimatic Variables Description

Variable Code	Variable Name	Variable description
BIO1	Annual Mean Temperature	The mean of all the monthly mean temperatures. Each monthly mean temperature is the mean of that month's maximum and minimum temperature.
BIO2	Mean Diurnal Range (Mean of monthly (max temp – min temp))	The annual mean of all the monthly diurnal temperature ranges. Each monthly diurnal range is the difference between that month's maximum and minimum temperature.
BIO3	Isothermality (BIO2/BIO7) (×100)	The mean diurnal range (parameter 2) divided by the annual temperature range (parameter 7).
BIO4	Temperature Seasonality (standard deviation ×100)	Returns the temperature coefficient of variation as the standard deviation of the monthly mean temperatures expressed as a percentage of the mean of those temperatures (e.g., the annual mean). For this calculation, the mean in degrees Kelvin is used. This avoids the possibility of having to divide by zero but does mean that the values are usually quite small.
BIO5	Max Temperature of Warmest Month	The highest temperature of any monthly maximum temperature.
BIO6	Min Temperature of Coldest Month	The lowest temperature of any monthly minimum temperature.
BIO7	Temperature Annual Range (BIO5-BIO6)	The difference between the Maximum Temperature of Warmest Period and the Minimum Temperature of Coldest Period.
BIO8	Mean Temperature of Wettest Quarter	The wettest quarter of the year is determined (to the nearest month), and the mean temperature of this period is calculated.

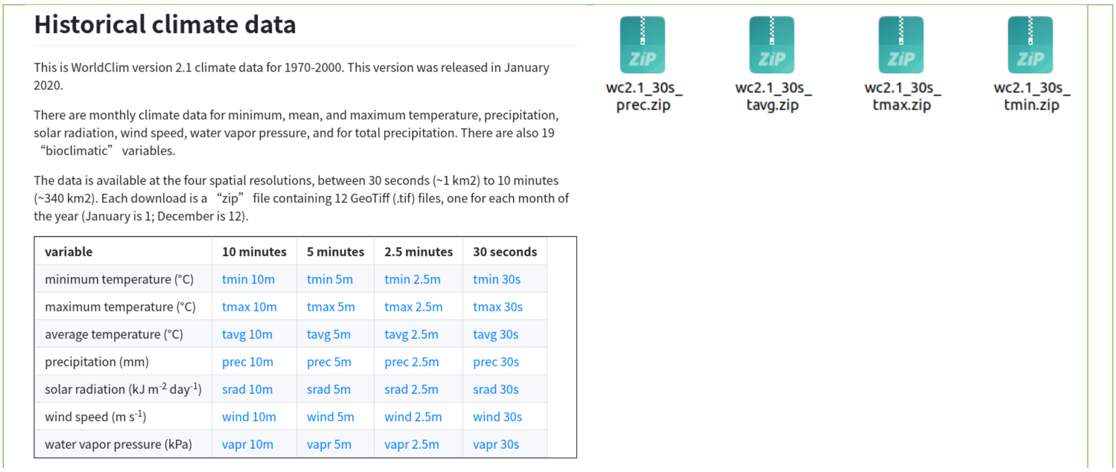
Variable Code	Variable Name	Variable description
BIO9	Mean Temperature of Driest Quarter	The driest quarter of the year is determined (to the nearest month), and the mean temperature of this period is calculated.
BIO10	Mean Temperature of Warmest Quarter	The warmest quarter of the year is determined (to the nearest month), and the mean temperature of this period is calculated.
BIO11	Mean Temperature of Coldest Quarter	The coldest quarter of the year is determined (to the nearest month), and the mean temperature of this period is calculated.
BIO12	Annual Precipitation	The sum of all the monthly precipitation estimates.
BIO13	Precipitation of Wettest Month	The precipitation of the wettest month.
BIO14	Precipitation of Driest Month	The precipitation of the driest month.
BIO15	Precipitation Seasonality (Coefficient of Variation)	The Coefficient of Variation is the standard deviation of the monthly precipitation estimates expressed as a percentage of the mean of those estimates (e.g., the annual mean).
BIO16	Precipitation of Wettest Quarter	The wettest quarter of the year is determined (to the nearest month), and the total precipitation over this period is calculated.
BIO17	Precipitation of Driest Quarter	The driest quarter of the year is determined (to the nearest month), and the total precipitation over this period is calculated.
BIO18	Precipitation of Warmest Quarter	The warmest quarter of the year is determined (to the nearest month), and the total precipitation over this period is calculated.
BIO19	Precipitation of Coldest Quarter	The coldest quarter of the year is determined (to the nearest month), and the total precipitation over this period is calculated.

By a quarter we should understand a period of any consecutive three months, not aligned to calendar quarters.

The method follows that of ANUCLIM software (Xu and Hutchinson, 2012), except that for temperature seasonality the standard deviation was used because a coefficient of variation does not make sense with temperatures between -1 and 1) (Harris *et al.,* 2014; Fick and Hijmans, 2017). A new global data set of bioclimatic indicators is presented in the work of Noce *et al.,* 2020. The data are available in NetCDF4 format at PANGAEA:
https://doi.pangaea.de/10.1594/PANGAEA.904278?format=html#download.

- Download needed data - for this exercise we will need historical average climate data for 1970-2000. Download minimum temperature (°C), average temperature (°C), maximum temperature (°C) and precipitation (mm) data sets with 30 seconds resolution (Fig. 12.3)
- Download page: https://worldclim.org/data/worldclim21.html. (Harris *et al.,* 2014; Fick and Hijmans, 2017)
    - https://biogeo.ucdavis.edu/data/worldclim/v2.1/base/wc2.1_30s_tmin.zip

  - https://biogeo.ucdavis.edu/data/worldclim/v2.1/base/wc2.1_30s_tmax.zip
  - https://biogeo.ucdavis.edu/data/worldclim/v2.1/base/wc2.1_30s_tavg.zip
  - https://biogeo.ucdavis.edu/data/worldclim/v2.1/base/wc2.1_30s_prec.zip
- Beware, data sets can be quite large ~ 14.1 GB



Historical climate data

This is WorldClim version 2.1 climate data for 1970-2000. This version was released in January 2020.

There are monthly climate data for minimum, mean, and maximum temperature, precipitation, solar radiation, wind speed, water vapor pressure, and for total precipitation. There are also 19 "bioclimatic" variables.

The data is available at the four spatial resolutions, between 30 seconds (~1 km2) to 10 minutes (~340 km2). Each download is a "zip" file containing 12 GeoTiff (.tif) files, one for each month of the year (January is 1; December is 12).

variable	10 minutes	5 minutes	2.5 minutes	30 seconds
minimum temperature (°C)	tmin 10m	tmin 5m	tmin 2.5m	tmin 30s
maximum temperature (°C)	tmax 10m	tmax 5m	tmax 2.5m	tmax 30s
average temperature (°C)	tavg 10m	tavg 5m	tavg 2.5m	tavg 30s
precipitation (mm)	prec 10m	prec 5m	prec 2.5m	prec 30s
solar radiation (kJ m^{-2} day^{-1})	srad 10m	srad 5m	srad 2.5m	srad 30s
wind speed (m s^{-1})	wind 10m	wind 5m	wind 2.5m	wind 30s
water vapor pressure (kPa)	vapr 10m	vapr 5m	vapr 2.5m	vapr 30s

Fig. 12.3 WorldClim Data Download Page and Downloaded Datasets

- Extract the four ZIP files into the working directory
- Each ZIP file contains spatial data in GeoTiff (.tif) geospatial raster format
- Given that the data sets have global coverage, being thus quite voluminous and then difficult to process, we will first proceed to extract a portion of the input raster
- For this we will use the Clip Multiple Layers plugin (Fig. 12.4)

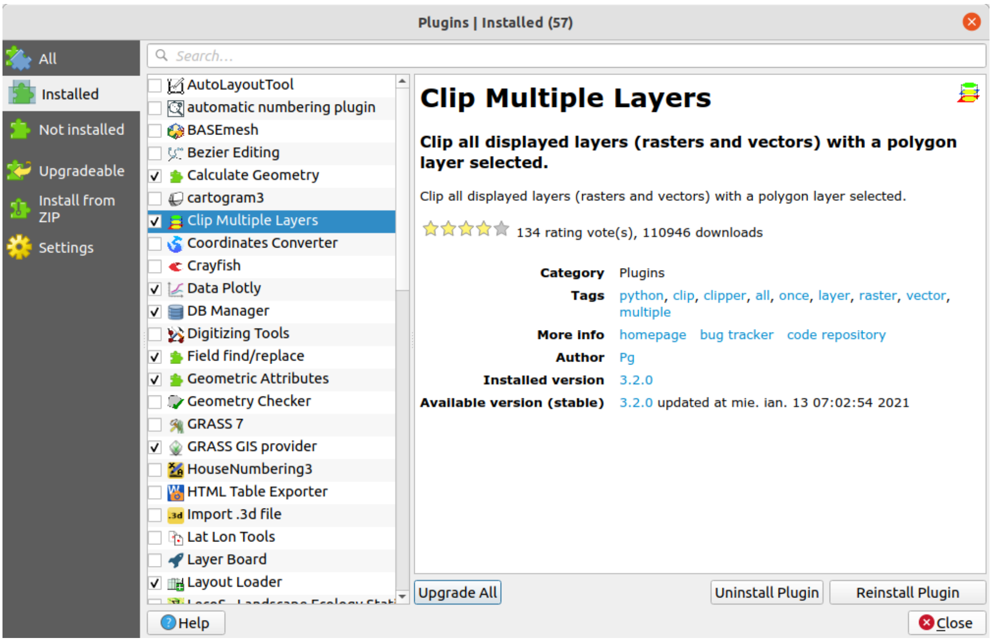


Fig. 12.4 QGIS Manage and Install Plugins dialogue is to be used to install the plugin

- To run the Clip Layers operation, vector polygon layers are needed. For this purpose, we need to download an appropriate set of data
- A good source of raster and vector GIS data is the free repository of R. T. Wilson, where data on Physical Geography (DEM, Hydrology, Soil, Climate/Meteo, Natural Disasters, etc.) and Human Geography (Socioeconomic, Place Names, Admin Boundaries) can be found http://freegisdata.rtwilson.com
- Download Admin 0 – Countries dataset at 1:10,000,000 Scale from Natural Earth public portal (https://www.naturalearthdata.com/)
- You can use this direct link: https://www.naturalearthdata.com/http//www.naturalearthdata.com/download/10m/cultural/ne_10m_admin_0_countries.zip
- Unzip and load the vector polygons dataset into QGIS
- Select the country for which you are interested in calculating Bioclimatic Variables
- Right-click on *ne_10m_admin_0_countries.shp* layer in QGIS Layers Panel and select *Export* ► *Save Selected Features as...* (Fig. 12.5)

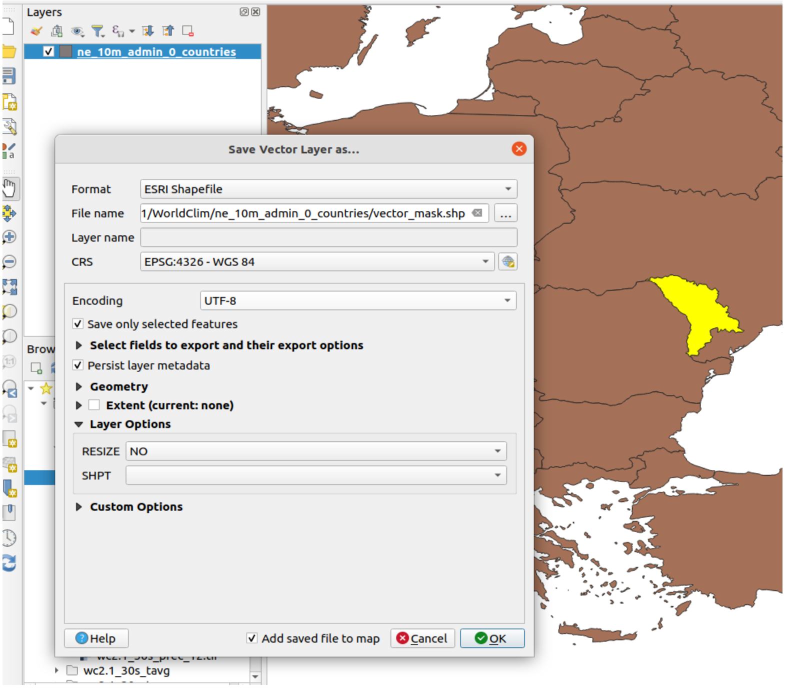


Fig. 12.5 Exporting selected polygon to a new ESRI Shapefile vector dataset (vector_mask.shp)

- The vector mask.shp will be added to QGIS
- Install the Clip Multiple Layers plugin (Fig. 21.6)

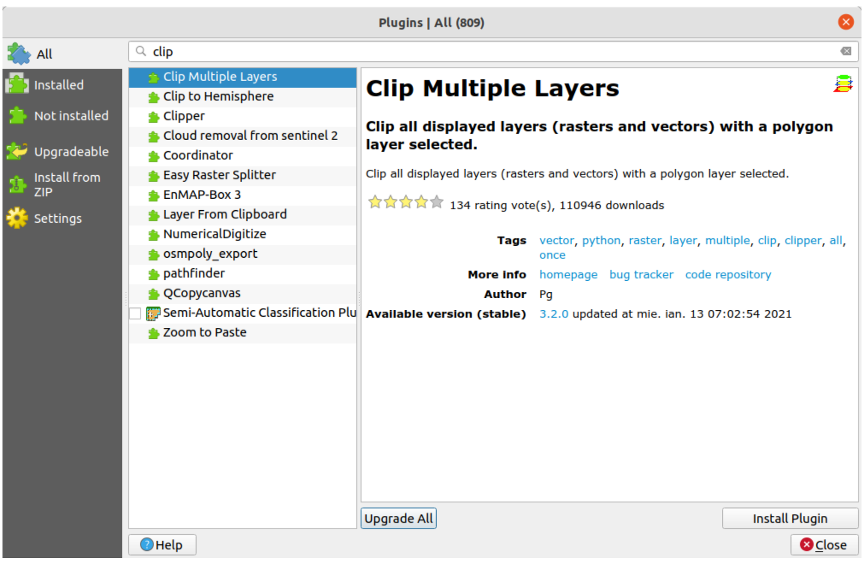


Fig. 12.6 Installing Clip Multiple layers plugin using Manage and Install Plugins Dialog

- Load your raster data (Fig. 12.7)

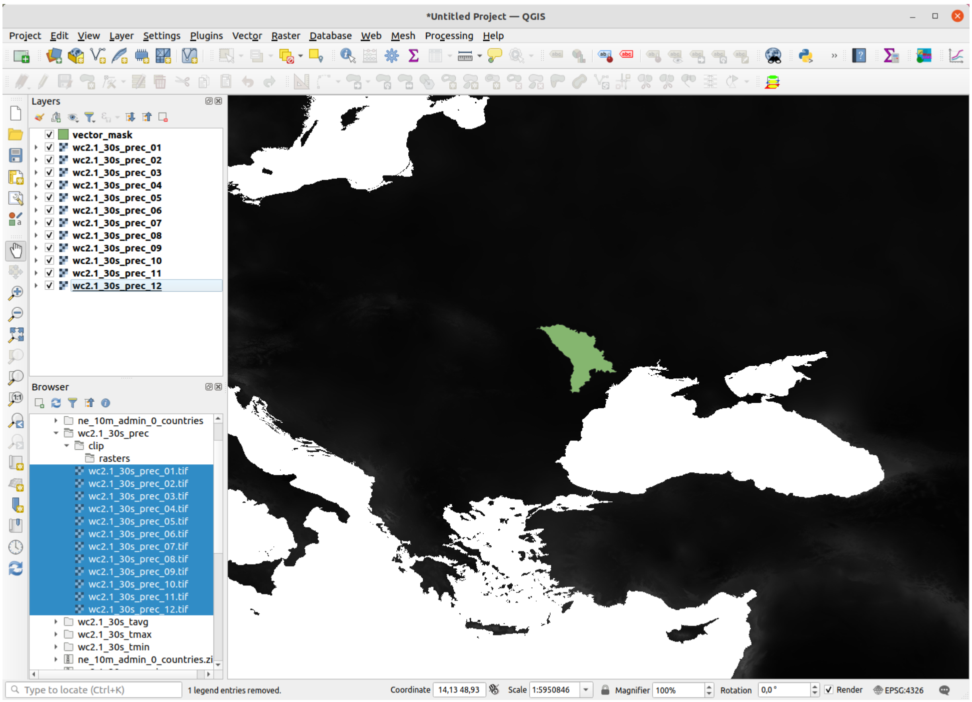


Fig. 12.7 Clipping mask and raster data loaded into QGIS

- Load and run the plugin to clip your rasters (Fig. 12.8)

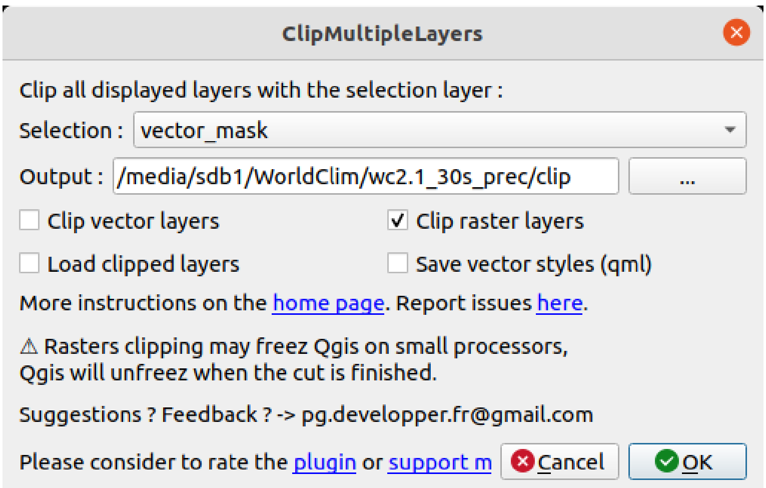


Fig. 12.8 Settings for Clip Multiple Rasters Plugin

- Repeat the clipping operation for each raster group (tmin, tmax, tavg and prec). You do not need to upload the clipped data to QGIS. But if you want to check them out, you can (Fig. 12.9)

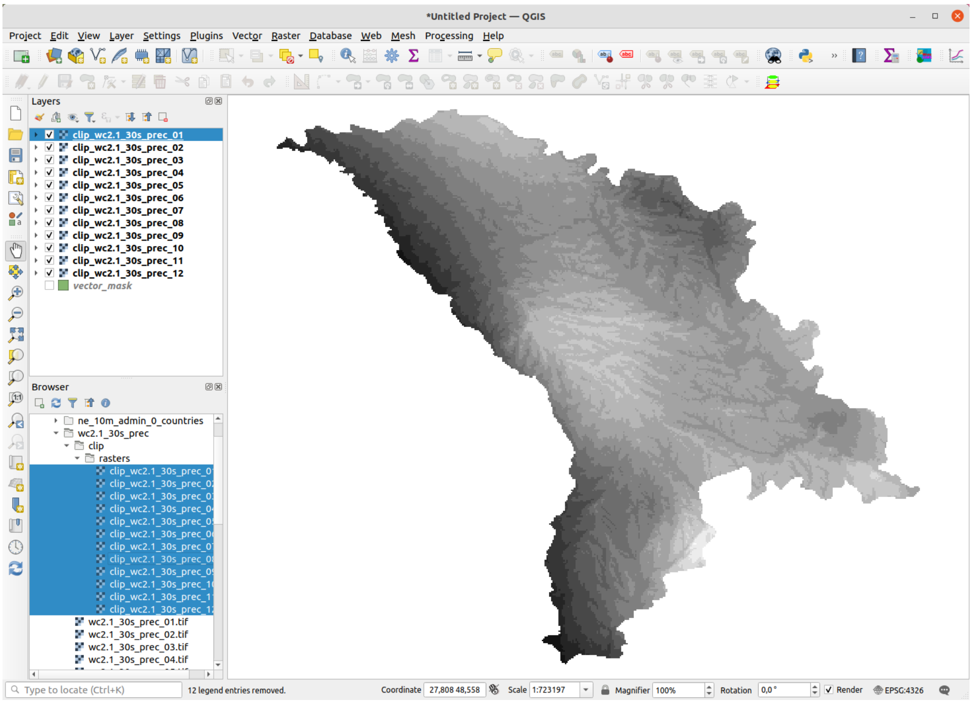


Fig. 12.9 Precipitation 12 clipped datasets (numbers in layers names correspond to months numbers)

- Once all the rasters are clipped by the mask polygon, we can start the calculation of Bioclimatic Variables
- Launch Bioclimatic Variables Tool and set it as follows (Fig. 12.10)

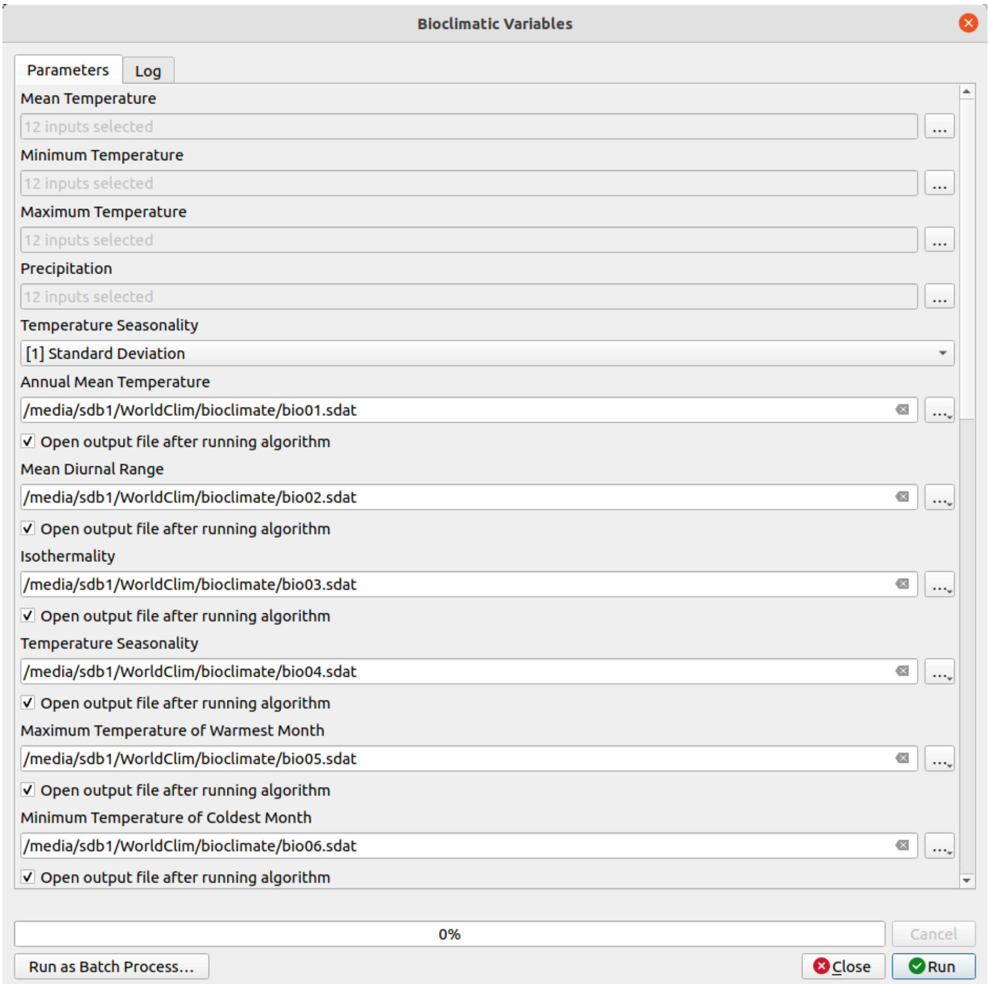


Fig. 12.10 Bioclimatic Variables Tool with all parameters set

- Set your input files (clipped raster). As you can see, for each rasters group (Mean Temperature, Minimum Temperature, maximum Temperature and Precipitation) all 12-month raster will be used. To select them, click on the Browse button on the right
- Set the output 19 rasters. You may notice that the output rasters will be saved in SAGA raster format (.sdat)
- Processing might take a while (Fig. 12.11)

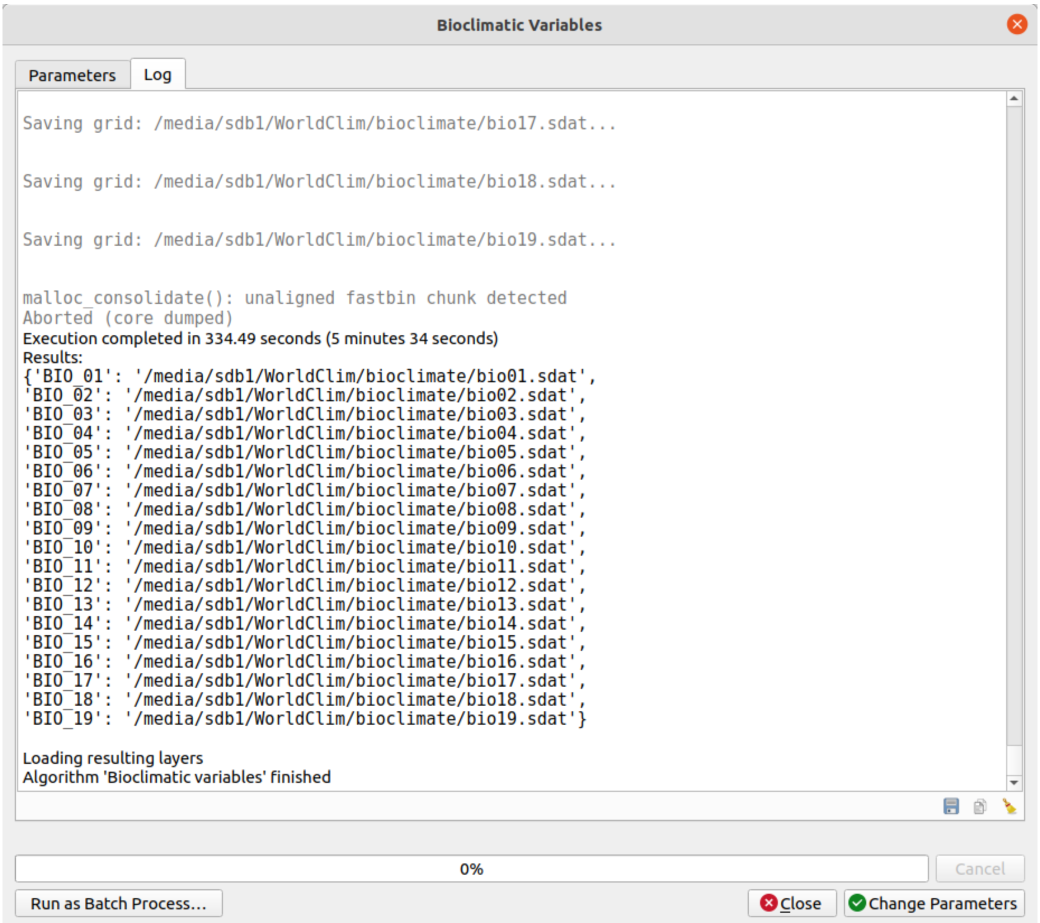


Fig.12.11 Processing. (5 minutes 34 seconds)

- Once the algorithm is finished, data will be loaded into QGIS (Fig. 12.12)

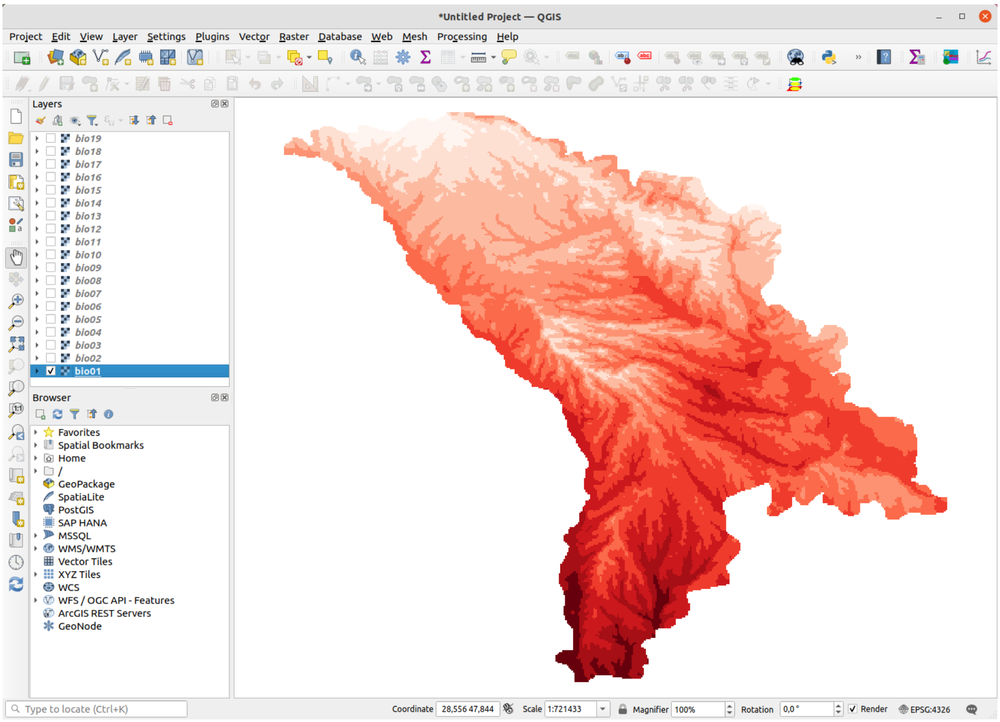


Fig. 12.12 QGIS GUI with BIO01 dataset (Annual Mean Temperature) loaded and styled

12.3 Calculation of Drought Indices using QGIS

Indicators are parameters used to describe drought conditions: rainfall amount, snow thickness, temperatures, surface runoff, groundwater and lakes water level, soil moisture, and so on. Indices are numerical representations of drought severity, assessed based on climatic or hydrometeorological indicators, such as those listed above (WMO, 2016).
Indices are used to provide a quantitative assessment of the severity, location, timing, and duration of drought events. Severity refers to the departure from the normal of an index. A threshold for severity may be set to determine when a drought has begun when it ends, and the geographic area affected. Location refers to the geographic area experiencing drought conditions (WMO, 2016).

12.3.1 Aridity “De Martonne” Index (AI)

The index was developed by E. de Martonne in 1925. The aridity is defined as the ratio between the amount of precipitation and the average temperature. Usually, AI is used to determine the development of drought conditions over short time periods. It can also be used for the classification of climates of different regions. The monthly calculation of AI can provide usefull information on droughts beginning.

The index may be as presented in the following equation:

$$AI=Pa/(Ta+10)$$

P_a is the annual amount of rainfall (in millimetres) and
T_a is the mean annual air temperature (in degrees Celsius)

Input parameters: Monthly mean temperature and precipitation. For climate classification, annual values are used. We will use data files generated before (Bioclimatic Variables 1 and 12):

- Launch QGIS
- Add two rasters in QGIS (Fig. 12.13)
    - BIO1 – Annual Mean Temperature
    - BIO12 – Annual Precipitation

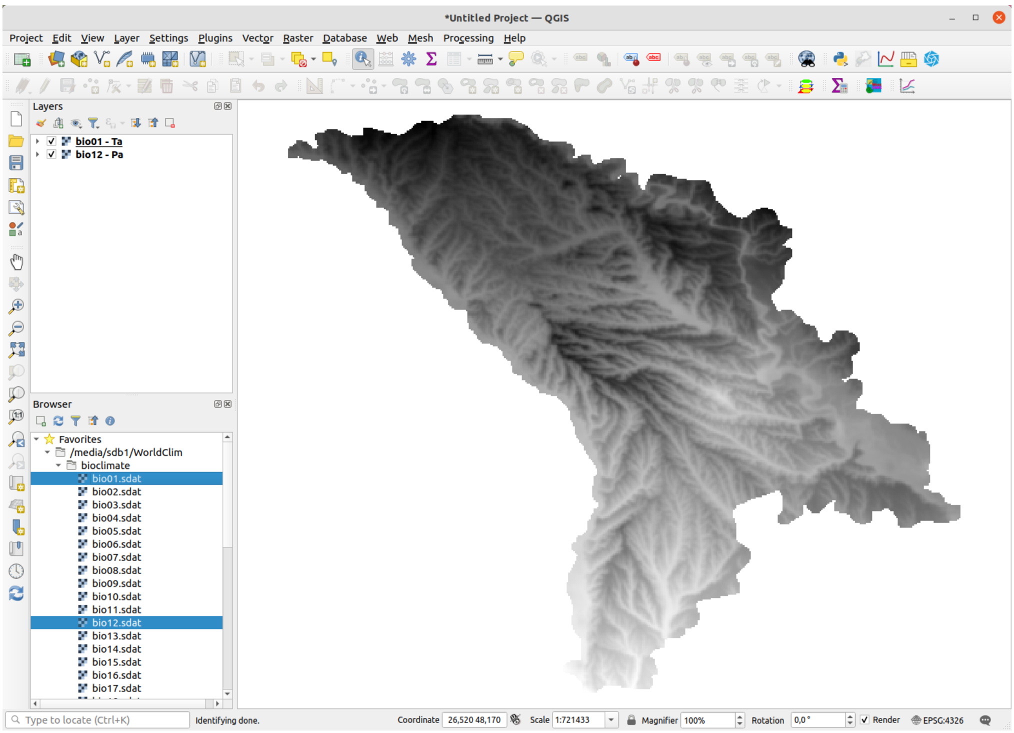


Fig. 12.13 BIO1 – Annual Mean Temperature and BIO12 – Annual Precipitation added to QGIS

- Launch Raster Calculator from Raster Menu (Fig. 12.14)
- Insert the next string: "*bio12 - Pa@1"/ ("bio01 - Ta@1"+10*) in the Raster Calculator Expression area.
- Set output file as: AI.tif
- Click OK

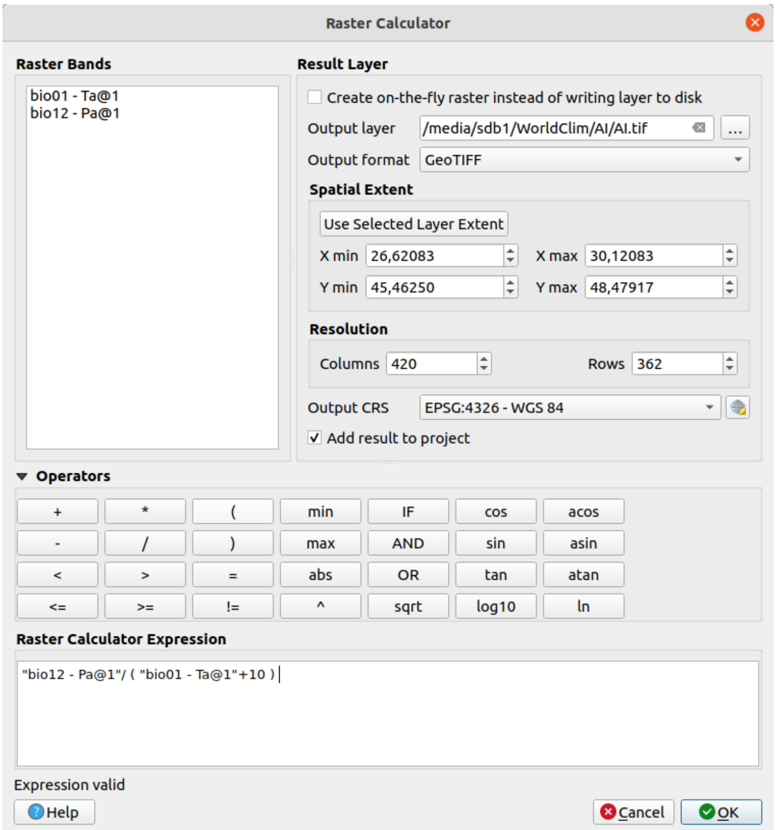


Fig. 12.14 Raster Calculator

- Generated AI map will load automatically in QGIS (Fig. 12.15)

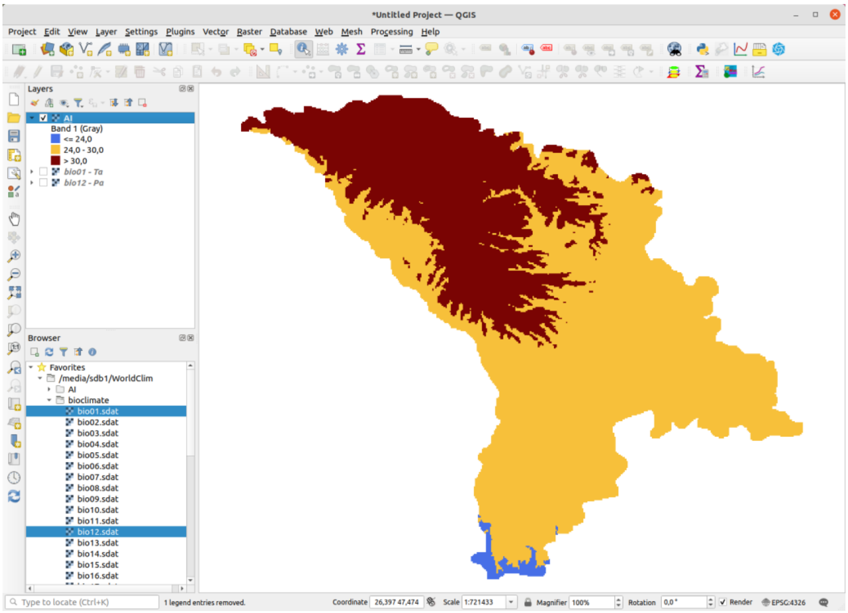


Fig. 12.15 AI classified raster loaded in QGIS

- You can interpret the data using the legend below (Table 12.2)
- In our case, we can see that values represent 3 climate types: Semi-arid, Moderately-arid and Slightly-arid

Table 12.2 De Martonne Aridity index values

Type of climate	AI Values
Semi-arid	15 ≤ I ≤ 24
Moderately-arid (Mediterranean)	24 ≤ I ≤ 30
Slightly-arid	30 ≤ I ≤ 35
Moderately-humid	35 ≤ I ≤ 40
Humid	40 ≤ I ≤ 50
Very-humid	50 ≤ I ≤ 60
Excessively-humid	60 ≤ I ≤ 187

12.4 Interpolation techniques in QGIS

Many real-world phenomena have a continuous distribution: heights, temperatures, precipitation, etc. It is practically impossible to measure these parameters continuously, over the whole area of interest, in order to generate areas used for further analysis and modelling. Thus, the measurements are performed at some points distributed regularly or randomly in the study area, and the intermediate values are derived during the interpolation process. Interpolation is a set of GIS methods that are used to create a continuous surface from discrete point data. In QGIS, interpolation is done using various interpolation tools available in the Processing Toolbox (Fig. 12.16).

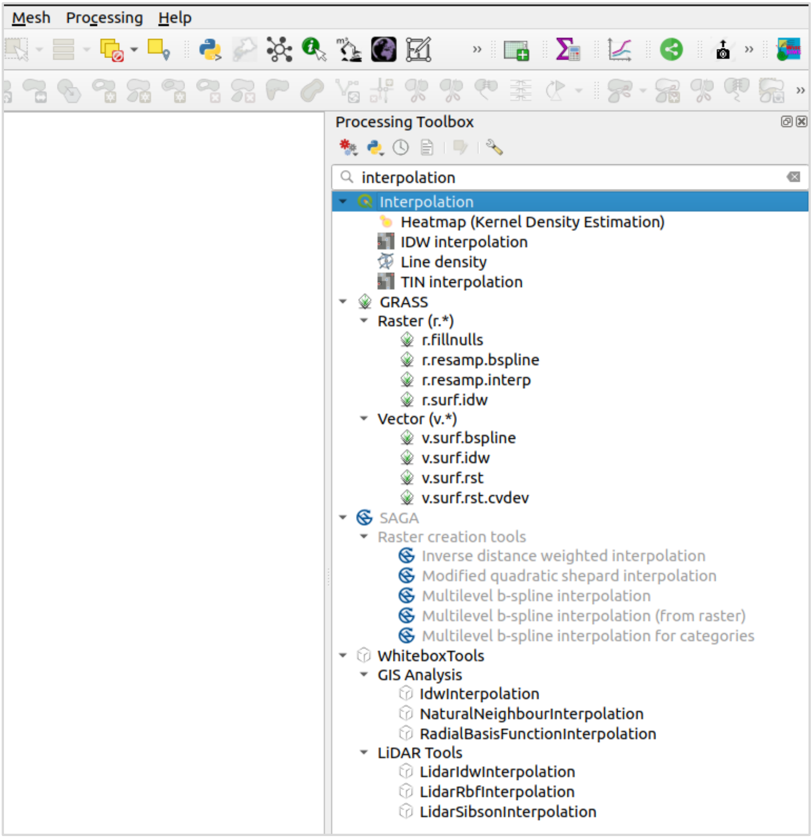


Fig. 12.16 Interpolation tools in QGIS Processing Toolbox

12.4.1 Interpolation methods

At present, there is a wide variety of interpolation methods, and this great variety only says that none of these methods are applicable in any situation. Interpolation methods fall into three main categories: deterministic, probabilistic, and combinations of those two. Deterministic methods (TIN, NN, IDW, Spline) create a continuous surface using only the geometric properties of point observations. Probabilistic methods (such as Kriging and Cokriging) allow variation to be taken in the interpolation process (Sluiter, 2009).

Deterministic methods can be divided into two groups: global and local (https://pro.arcgis.com/). Global interpolation methods generally produce smoother surfaces (Sluiter, 2009). Interpolation methods can also be divided into: exact methods (B-Splines and Kriging) and approximate methods. Exact methods reproduce the original values at the data points on which the interpolation is based, while approximate methods do not reproduce the original values and reduce errors due to the smoothing effect (Sluiter, 2009). The most used interpolation methods are TIN, IDW, various Kriging techniques and other methods.

- TIN interpolation - the TIN method allows the creation of a surface formed by triangles between the nearest neighbouring points (Fig. 12.17). To do this, circles are created around the selected sampling points, and their intersections are connected in a network of non-overlapping triangles as compact as possible. The resulting surfaces are not very smooth (QGIS User's Guide).

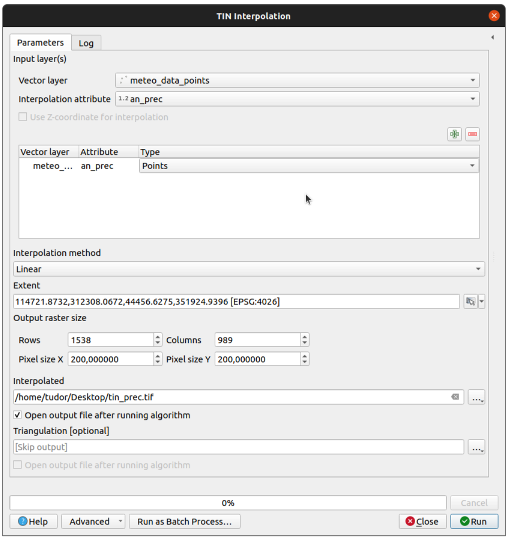


Fig. 12.17 Creating Annual precipitation Grid using TIN method in QGIS

- Nearest Neighbourhood - in QGIS this method does not perform any interpolation or smoothing, but only takes the value of the nearest point found in grid node search ellipse and returns it as a result (Fig. 12.18). If no points are found, the specified NODATA value will be returned (QGIS User's Guide).

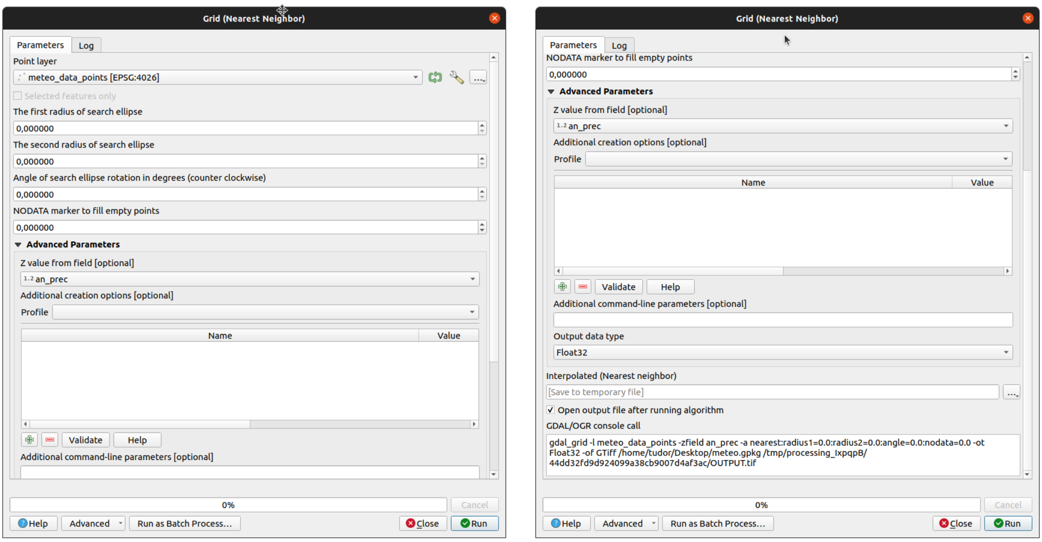


Fig. 12.18 Creating Annual precipitation Grid using Nearest neighbor method in QGIS

- IDW interpolation - during interpolation the sampling points are weighted so that the influence of one point on another decreases with the distance from the unknown point you want to calculate (Fig. 12.19). Like the TIN method, the IDW technique is relatively easy to apply and is widely available among common GIS software (QGIS User's Guide). When less than 30 measurements are available IDW or Splines may be a better choice (Sluiter, 2009).

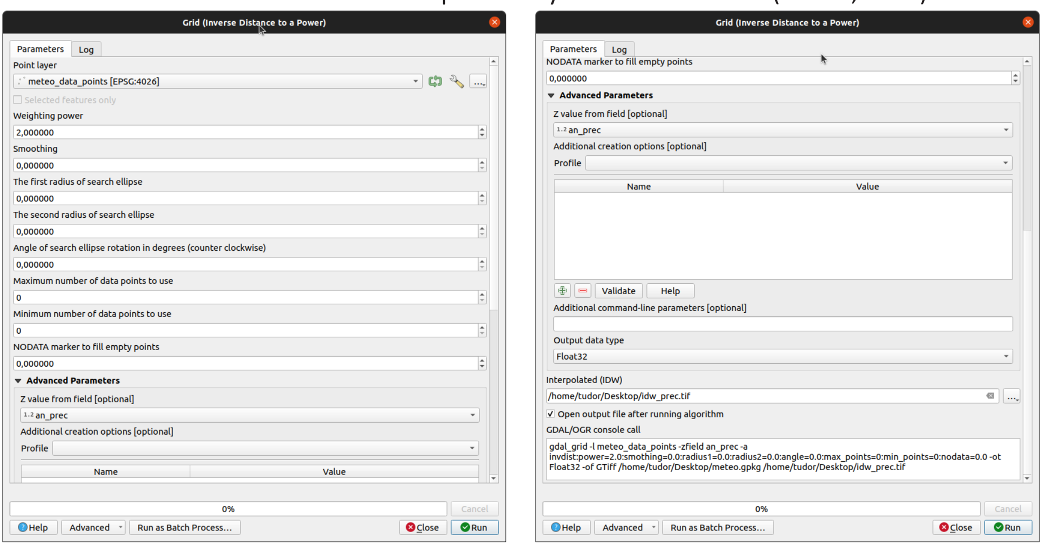


Fig. 12.19 Creating Annual precipitation Grid using IDW method in QGIS

- Kriging is the most commonly used geostatistical group of spatial interpolation methods. Kriging techniques are based on a spatial pattern between observations. The most important step in Kriging technique is the creation of variogram (Fig. 12.20). Kriging methods take into account the distance between observations (as in the IDW method), but also try to capture the spatial structure of the data by comparing pairs of observations separated by specific distances, to highlight the relationships between observations separated by different lag distances. Several variants of Kriging are known, such as Simple Kriging, Ordinary Kriging, Universal Kriging and Regression Kriging (Fig. 12.21). In QGIS, all these methods are provided by the SAGA GIS application, being available through the Processing Toolbox (Sluiter, 2009; Su-Na et al., 2010; SAGA GIS User Guide).

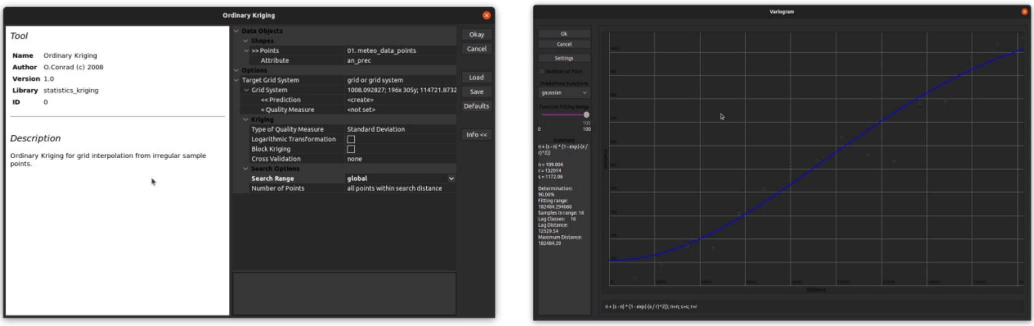
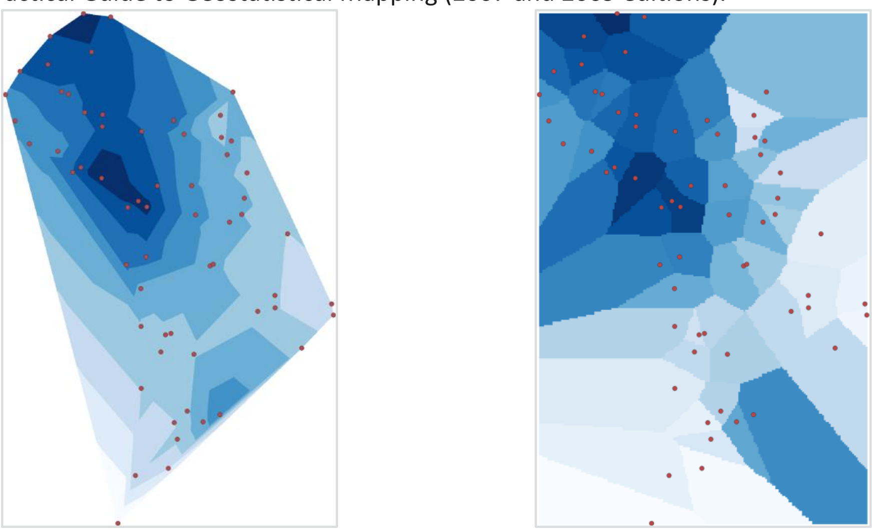
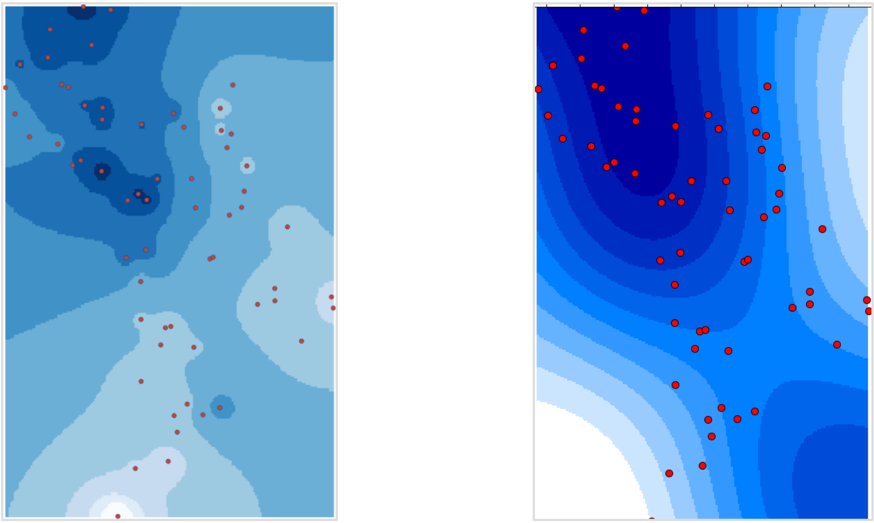


Fig. 12.20 Creating Annual precipitation Grid using Ordinary Kriging method in SAGA GIS

- For climatic variables, especially the ones derived from DEMs (Digital Elevation Models), the Regression-kriging method is recommended by many studies to calibrate the values using the real observations, and after that real deterministic models can be used to make predictions (Hengl, 2007). Regression-kriging use the auxiliary predictors (ex. elevation) to map climatic variables. Geostatistical interpolation methods are described in detail in Tomislav Hengl's book - A Practical Guide to Geostatistical Mapping (2007 and 2009 editions).



TIN NN



IDW | Ordinary Kriging

Fig. 12.21 Annual precipitation Grids generated by using 4 different methods

Ch12 Sources:

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